The Promise of Solid State Lighting for General Illumination

Light Emitting Diodes (LEDs) and Organic Light Emitting Diodes (OLEDs)

Conclusions and Recommendations from OIDA Technology Roadmaps Co-sponsored by DOE (BTS) and OIDA

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Executive Summary

In the midst of the rising fuel prices and the blackouts in California there is silent revolution in solid state lighting (SSL) that has the promise of replacing conventional light sources the way integrated circuits replaced electron tubes fifty years ago. The potential benefits of solid state lighting (SSL) are enormous.

1. It is estimated that by 2025 SSL could reduce the global amount of electricity used for lighting by 50%; no other electricity consumer has such a large energy-savings potential.

2. Most of the electricity comes from burning fossil fuel hence the reduction energy consumption results in reduced carbon-emission at the level of hundreds of million tons a year.

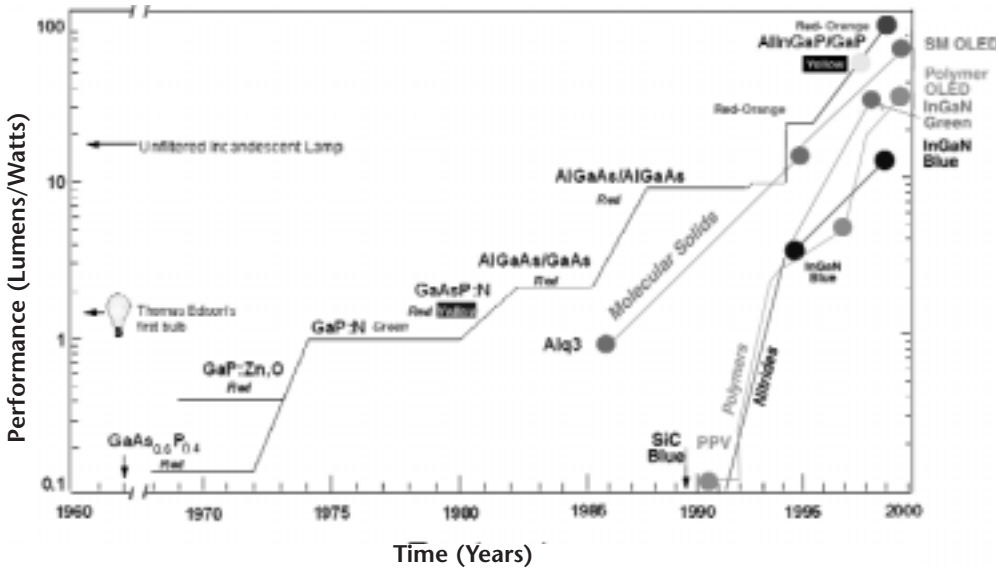
3. The cumulative savings potential in the US alone over 2000 - 2020 could amount to:

- Saving 16.6 Quads (760 GW) of electrical energy
- Eliminating 258 million metric tons of carbon emission
- Alleviating the need of 133 new power stations (1000 MW each)
- Cumulative financial savings of $115 Billion (1998 dollars).

4. And finally, SSL represents a new lighting paradigm that will create a new lighting industry of over $ 50 Billion/year worldwide. Flat arrays of inorganic LEDs or laminates of organic LEDs (OLEDs) can be mounted in any pattern or shape on floors, walls, ceilings, or even on furniture.

Light emitting diodes, LEDs, provide point sources such as incandescent lamps while organic LEDs, OLEDs might replace area sources such as fluorescent lamps. Both LEDs and OLEDs are currently under development for niche markets in signaling and display applications. These technologies had rapidly evolved over the last Decade as shown on the attached efficiency curves:

FIGURE 1
Performance Improvements of Inorganic & Organic LEDs



Feasibility demonstrations exist that both inorganic and organic light emitters can outperform conventional light sources and provide a new energy efficient lighting paradigm. Industries and governments recognize this worldwide. Major government sponsored industry consortia, to reduce energy consumption and to create a new lighting industry, already exist in Japan, Europe and Korea. Another is in a formative stage in Taiwan.

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

Both LEDs and OLEDs have commercial entry points in special niche applications. Neither technology is aimed, however, at general illumination where the major economic and environmental impacts will be realized.

It will take a major government sponsored industry driven initiative, involving academia and national laboratories, to accelerate the penetration of SSL into general illumination as depicted in the table below. Without such an initiative this technology and market will probably go to other countries where cooperative programs between industry and government already exist.

The Evolution of SSL Markets Assuming a Major Government Sponsored Initiative

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

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

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

PART 1
LIGHT EMITTING DIODES (LEDS)

Technology Roadmap for Light Emitting Diodes (LEDs)

Conclusions and Recommendations

On October 26 and 27, 2000, a workshop was held in Albuquerque, NM on LED based Solid State Lighting (SSL) for General Illumination. Approximately ninety representatives participated from Industry, Government, National Laboratories, and Universities. The workshop was co-sponsored by the Department of Energy (BTS) and OIDA.

Technology Roadmap Process

OIDA Technology roadmaps are intended to identify the technologies required to exploit market opportunities. Emphasis is on pointing to the weak links of the "food chain" through comparing needs and available resources. They are developed with the help of experts representing industry, national laboratories, and academia. OIDA seeks to achieve a consensus view based on open discussions in a workshop environment that helps to network the North American industry.

The process begins with the identification of experts in the field from industry, national laboratories and academia who can contribute to a strawman report. A designated expert in the field (facilitator) generates a preliminary report including available information and inputs from various experts. This becomes the "strawman report" and it is exposed to the attendees of the workshop who can discuss, amend, and/or modify this report, thereby reaching an industry consensus.

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

- Improve efficacy at all visible wavelengths to obtain 2000 lumen/Watt white-light sources.
- Reduce the cost of solid state light sources so as to be competitive with traditional light sources.
- Explore the opportunities to develop new technologies and products leading to a new lighting industry enabled by the attributes of SSL-LED, such as surface mounted "smart" light sources.

Summary of Workshop Conclusions and Recommendations

A series of breakout sessions were held at the LED workshop to develop an industry consensus on the issues and roadblocks for the successful realization of LED based general illumination. A summary of some of the more important determinations and

recommendations made by the workshop attendees are presented in the following sections:

A) describes the three current strategies for achieving white light with LEDs.

(B) enumerates the long term research issues, and

(C) presents topics that are specific to the nitride and phosphide LED alloy systems as well as issues for wavelength conversion phosphors.

(D) shows the program for the workshop.

A. Strategies for Solid State Lighting for General Illumination

Currently, there are three viable options achieving LED-based SSL white lighting.

1. Blue LED with phosphor(s),
2. UV LED with several phosphors, and
3. Three or more LEDs of different colors.

It is generally acknowledged that The ultimate performance goal of 200 lm/W will be most readily achieved by option III. This option, however, poses many challenges and will be probably the last to reach commercial applications. Various issues of lifetime, stability, photon extraction, etc, are common to all SSL white light initiatives and will require research programs at industry, universities and/or national laboratories to solve these problems. Another long term research program involves increasing the wall-plug-efficiency of LEDs for all colors. The following sections outlines the pros and cons of each option.

1. Blue LED with phosphor(s)

At the present time, the blue LED plus phosphor strategy has the shortest time line for commercialization. Companies such as Nichia, CREE, and others, already have demonstrated "white-light" generation by using a blue LED and a single phosphor (YAG:Ce). Part of the blue light emitted by the LED escapes and another part is converted by the phosphor to an amber color. The amber colored light is the complimentary color of the blue light emitted by the LED, thereby producing white emission.

There are two principal problems with this approach,

- The "halo effect" and
- The low level of absorption of blue light by the phosphor.

Halo Effect: The "halo effect" or bleed-through effect occurs because the light from the blue LED is directional while the amber light from the phosphor radiates over a

2π solid angle. Thus, for an observer looking from the side, the color appears multi-color - not white.

Blue Light Absorption: The second problem is the limited blue absorption by the phosphor. For rare earth phosphors, the absorption in the blue is relatively weak, thus requiring "thick" phosphors. Long term research is necessary to either identify new phosphors with strong absorption in the blue or to identify a sensitizer ion to facilitate energy transfer to the rare earth ion. Current industrial research is concentrating on generating a 2π solid angle emission from the blue LED.

The blue LED approach is not limited to only one phosphor, it may be used with a two-component phosphor system (e.g. green and red) to generate high-quality white light and this also has been demonstrated experimentally. Further work is necessary to combat the "halo effect" mentioned above, as well as maintaining the highest possible conversion efficiencies. Furthermore, improving existing red and green phosphors or identifying new ones will be important in order to optimize quantum efficiency and stability with temperature.

In other approaches, a semiconductor or other luminescent material becomes the wavelength converter. For example, Professor Fred Schubert at Boston University used the semiconductor alloy AlInGaP as a "phosphor" to be pumped by a blue InGaN LED active region to generate two-color white light. A similar approach might be employed using quantum-dot nanoclusters or organic thin films. Much work is required before high-efficiency, high color-rendering white light will be achieved with these approaches.

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

2. UV LED plus three or more phosphors

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

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

3. Three or more LEDs of different colors

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

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

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

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

B. Long Term Research Issues

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

1. Materials Research and the Physics of Light Generation

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

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

During the first year an extensive analysis of existing materials should be carried out to catalogue the fundamental properties of these materials using existing techniques and models. On the three year time frame the optimized materials as well as new materials should be incorporated into optimized structures as determined by experiments coupled to advanced modeling. The fifth year should culminate with the introduction of devices with improved efficiencies.

2. Substrate materials

Currently there are at least three different substrate materials used to produce GaN-based LEDs, sapphire, GaN, and SiC. Each material system has its pros and cons but neither system provides a large area defect free substrate with good lattice match at a reasonable cost. A major effort is required to develop such an ideal substrate.

3. Reactor Design

The next area centers on epitexial reactor development. The current reactors are not very efficient, reliable and the results are not always reproducible. We need to gain a better understanding of the fundamental chemical reactions particularly for the growth of nitride materials to enable the design of better growth systems or new reactors. Also, detailed modeling of existing reactor fluid dynamics coupled to reaction chemistry should reveal weaknesses in the current designs.

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

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

4. Light Extraction

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

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

5. Photon Conversion Materials

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

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

6. Novel Concepts of Solid State Light Emission

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

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

7. Packaging

Packaging has an enormous impact on the efficiency, life and cost of LED devices. New packaging concepts must be explored to couple out more photons, to provide color mixing, to incorporate control circuits and to assure long operating life. However, it is difficult at this time to address all issues of packaging until the final LED design strategies are well defined.

8. Lighting Infrastructure

It should be noted that light bulbs represent only one third of the $40 Billion lighting market. A larger segment of the market involves powering, fixtures, light distribution, etc. A separate efforts is needed at developing building and lighting architectures that could, at a system level, exploit the unique characteristics of solid state lighting while still appealing at a consumer level to human ergonomics. Many of these efforts are already ongoing (e.g., the RPI lighting research center, Lawrence Berkeley's Lighting Research Center, and other efforts connected to the US Department of Energy's Office of Building Technology, State and Community Programs), and should be expanded to include broader industry participation in a forward-looking R&D on solid state lighting.

C. Critical Issues and Research Opportunities for Nitride and Phoshide-Based LEDs and Wavelength Converters

A summary is presented for the three important LED SSL subject areas: Nitrides, Phosphides, and Phosphors. For each subject, specific tasks are identified.

Nitride-based LEDs

Although the InGaN system has been known for many years, it has reached major commercial success only over the past five years through the achievement of high intensity blue LEDs. This material system is much harder and requires high temperature operations compared to the phosphide based LEDs. It therefore requires a different technology which has yet to be developed. This material system has been

exploited to produce green to UV emitters, but it is conceptionally capable of covering the entire visible spectrum. A long-term goal could include the development of all light sources with one system.

The critical challenges for AlGaInN systems are in five main areas:

- Large area bulk substrates
- Low cost methods for improved light extraction efficiency
- Increased external quantum efficiency
- Lifetime and lumen maintenance
- Color mixing and high power

Phosphide-based LEDs

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

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

Wavelength Converters

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

- Development of new inorganic phosphors for near UV (360-410nm) and blue(>410nm).
- Development of new organic phosphors: near UV (360-410nm) and blue(>410nm).
- Improvement of the absorption of the LED light (blue or UV) by the various phosphors.
- Achievement of > 90% internal quantum efficiency in blue, green, and red phosphors (or other luminescent materials).
- Exploration of quantum dots and nanoclusters for wavelength conversion.
- Control of degradation mechanisms under high-current, high-temperature operation.
- Reduction of ambient sensitivity of phosphors and the development of new application techniques.

This is in a nutshell the set of conclusions and views presented at the Workshop by a variety of participants. Without exception, all agreed that a properly formulated government sponsored initiative is needed to provide a significant boost to the research and development of LEDs for general lighting and assure the US leadership in this field.

Part 2
Organic Light Emitting Diodes (OLEDs)

Technology Roadmap for Organic Light Emitting Diodes (OLEDs)

Conclusions and Recommendations

On Nov 30 – Dec 1, 2000, a workshop was held in Berkeley, CA on OLED based Solid State Lighting (SSL) for General Illumination. Approximately fifty-four representatives participated from Industry, Government, National Laboratories, and Universities. The workshop was co-sponsored by the Department of Energy (BTS) and OIDA.

Summary of Workshop Conclusions and Recommendations

The technology roadmap process is described under the LED workshop on p. 5.

A series of breakout sessions were held at the OLED workshop to develop an industry consensus on the issues and roadblocks for the successful realization of OLED based general illumination. A summary of some of the more important determinations and recommendations made by the workshop attendees are presented in the following sections:

A. Device Performance

Several major issues have been identified that stand in the way of successful commercialization of OLEDs for general lighting. Solving of each of these issues will require a series of incremental improvements / inventions. The major issues are:

1. Consensus on opportunities and challenges.
2. Low efficiency of existing OLED devices.
3. Insufficient operating life of OLEDs.
4. The absence of acceptable white color with high CRI (Color Rendition Index).
5. High cost
6. Inadequate infrastructure

In the following, the Workshop conclusions relative to the above issues and the proposed course of action is discussed.

1. Consensus on Opportunities and Challenges

It is the opinion of the OLED Workshop participants that there exists an unparalleled opportunity to develop OLEDs for general lighting applications. No fundamental or

theoretical obstacles now exist that would prevent OLEDs from achieving the goal of becoming the commercial source of light.

However, even though *fundamental* roadblocks do not exist, many incremental advances in technology, most of them requiring inventions, must be made. These advances, which can overcome what can be called *"incremental roadblocks"*, will happen only if substantial research is devoted to the understanding and development of OLEDs and particularly to the design and synthesis of a vast array of novel high performance materials. The lack of high performance materials (charge transport small molecules and polymers, singlet and triplet emitters with the right emission spectrum, etc.) is the major obstacle in achieving the goal.

The use in displays is considered to be the first step for future applications of OLEDs. The companies that develop displays may focus their effort towards OLEDs for general lighting, only after commercial success in displays. The focus on displays to some extent slows down the development of OLEDs for general lighting because the priorities are different.

Although the views of the individuals of the workshop varied, it was a general consensus that without a meaningful industry / government / academia collaboration and a substantial infusion of funds it would take at least 12 – 15 years before the commercialization of OLEDs for general lighting could be considered in the USA. In that case, it is generally believed that Japan or Europe would be far ahead of the US and take the leadership role. However, it is believed that with appropriate incentives, financial stimulation and within the properly formulated framework of industry / government / academia collaboration, the OLEDs could be developed within 5-8 years for the use in general lighting, and the US leadership could be assured.

2. Low Efficiency of Existing OLED Devices

No fundamental insurmountable roadblocks have been identified. In fact, given recent quantum efficiency and drive voltage improvements, it is recommended that the application for general lighting be pursued aggressively as soon as possible. To illustrate the point, the individual processes controlling the device quantum efficiency, the status of the process elements and the outlook for the future will be discussed here.

The OLED internal efficiency η_{int} is the number of generated photons per number of injected charge pairs. Ideally, it is desirable that all injected charge pairs result in generation of photons. Unfortunately, the detailed processes leading to the creation of photons are still inefficient. These processes are:

a) the charge balance factor γ (a fraction of injected charges that produce excitons),

b) the singlet excitation efficiency η_s (the fraction of excitons that are formed as singlets), and

c) the quantum efficiency of fluorescence Φ_f.

The charge balance factor γ can approach unity if the hole injection is balanced with the electron injection by an appropriate choice of injecting electrodes and charge transporting materials. Unequal injection rates result in a free passage of one sign carrier and thus to wasteful passage of current. Progress in this area has been mainly empirical but matching the work functions of the injecting electrodes with the reduction or oxidation potentials of the charge transporting materials is the key to success. *In the current best OLED devices, γ is near unity.*

It turns out that the existing electrode materials are not optimal for OLEDs for lighting. They are either too resistive, too brittle, or chemically too reactive, or too light absorbing. Similarly, the charge transport materials are electrochemically unstable or deficient by other accounts. All these materials must be eventually replaced and the whole optimization process must be done again.

Based on a spin statistics, the singlet excitation efficiency hs was believed to have a maximum value of 25%. In other words, only 25% of excitons were supposed to be singlets, which may be capable of relaxing the energy as photons. The remaining 75% of the excitons would result in triplet states. This was thought to impose a 25% fundamental limit on the internal quantum efficiency of electro*luminescence*.

However, recent studies show that this "law" is no longer valid; singlet excitation efficiencies in excess of 35% have been identified and verified. This opens a new area of research that has to be undertaken in order to improve the device efficiency even further. No one can predict what the ultimate limit could be, but values close to unity could be contemplated and are viewed as possible.

Furthermore, also recently, experiments showed that triplets could be harvested as well, as photon emitting species. Phosphorescing dopants containing heavy metals proved to be useable in selected cases, and the overall excitation efficiency was shown to be in excess of 25%, breaking the "old" rule that triplet excitation is useless in producing photons. This discovery again opens a new field of research, conceivably raising in the future the overall excitation efficiency to near unity.

The quantum efficiency of fluorescence Φ_f (the fraction of excitations that result in the formation of either singlets or triplets) can also approach unity but only in dilute solutions. Typically, a large fraction of excitations release the energy as heat. General problem is to maintain high Φ_f in solid state. Few materials have Φ_f greater than 50% in OLEDs. However, progress has been made in this area as well. For example, greater fluorescence efficiency in small- molecular devices is achieved by introducing additional dopants — for example quinacridone to the host Alq_3. Again, substantial research is due.

Other causes of poor Φ_f are purely photonic effects. It appears that proximity to mirror-like metal electrode enables energy transfer from exciton to surface plasmon, or the suppression of photon field near metallic mirror reduces the radiative emission. The optimum spacing between the emissive zone and the cathode — determined in a model experiment using SiO_2 spacer — is of the order of 50 nm. The quantum efficiency of fluorescence Φ_f can be reduced by a factor of 6 if the emissive zone is closer

to or farther away from the metal. Factors such as this have to be considered in designing the OLED devices. This and similar effects have to be also researched.

The internal device efficiency η_{int} is a product of these three factors:

$$\eta_{int} = \gamma \eta_s \Phi_f$$

It is now quite likely, in view of the recent development, that the internal device efficiency can be eventually raised to values that are close to the fundamental limit of unity (100%). Substantial progress has been already made in increasing the internal device efficiency, albeit in isolated cases. Significant research is now needed to expand the knowledge of these processes and in the design and development of novel emitters and sensitizers that are not only efficient, but that would allow selection of color and be stable at the same time.

In addition to the internal inefficiencies, there exists a problem with the "extraction" of photons from the device. Over 80% of the light has been typically lost to internal absorption and waveguiding in a simple planar device. The internal reflection of photons caused by high refractive indices of the layer materials is the main cause of poor extraction efficiency. Only a fraction of generated photons now makes it out of the device.

(The external efficiency next is related to the internal efficiency by a formula

$$\eta_{ext} = R_e \eta_{int}$$

where R_e is the extraction efficiency. Obviously, there is a need to increase R_e to the maximum possible value).

Even here, the optimism that the extraction efficiency can be improved, is justified. For example, the extraction efficiency R_e (the number of photons emitted to the exterior of OLEDs per number of photons generated inside the device) for isotropic (small molecular) systems has already been raised from about 18% to 35%, and in the case of polymeric emitters, to 45%. This was achieved by proper engineering the conductor (electrode) surface pattern. In these experiments it was shown that by changing the reflective pattern the photons could be redirected to reach the "escape cone" and leave the device.

Some members of the team believe that the extraction efficiency can be increased above 80% with appropriate patterning of the reflective substrate. The ways of maximizing the escape probability have to be modified and manufacturing procedures to achieve the highest extraction have yet to be identified.

There was much discussion regarding the luminance level required. If the entire ceiling is emitting, a luminance level of 100 cd/m^2 is necessary (this will give 100 cd/m^2 at desk level if room is large). For a portion of the ceiling (such as in a common office), the needed luminance is near 1000 cd/m^2. The lighting industry will not accept greater than about 850 cd/m^2 for glare reasons and, for 850 cd/m^2, approximately 12% of the ceiling area would be required for lighting. *A luminance level of*

It has to be noted that all the above advancements have been made in isolated cases, certainly not at the same time.

Raising the internal device efficiency to near unity and improving the extraction efficiency to perhaps >80% would make the OLED devices by far the most efficient light sources.

850 cd/m^2 was decided to be the target for efficiency and stability calculations.

The short term efficiency target is >100 lm/W. To achieve this target, a needed efficiency improvement of 2x, 3x and 4x for G, R, and B, respectively, is estimated. A 60 – 100 Lm/W white light source was considered achievable by 2005 - 6, given appropriate funding.

3. Insufficient Operating Life of OLEDs

It was not clear to the participants how to define the useful life of OLEDs. After a long discussion, it was agreed that a minimum of 10,000 hrs is needed, with a 20% max. loss of luminance at 850 Lm/W for all colors. This is the first level target, which has to be reached to assure the competitiveness with fluorescent lighting.

Short device life is a major obstacle to commercialization of OLEDs for general lighting. As mentioned above, this is not a priority in display applications, where the current lifetimes are already close to the desired values. Consequently, there is no systematic highly focussed research going on that would address this issue and the targets for device life will not be reached without a major inducement. It was felt that here lies a prime opportunity for the industry — government — academia collaboration.

There is no single cause that would limit the useful life of the OLED devices. Among the factors that are known to limit the device life are:

a) Reactions with the ambients (oxygen, CO_2 and moisture) involving the electrode metals, charge transporting small molecules and polymers, excitons, and dopants;

b) Electrochemical degradation (reduction or oxidation) involving the electrode-transport interface, charge transporting small molecules and polymers, excitons, emitters and dopants;

c) Spontaneous (thermal) statistical conversions / decay of the charged species (charge transporting small molecules and polymers) and excitons.

It is also known that emitters of different color age with different rates, which means that the quality of white color will deteriorate with time, unless the aging rates are brought to the same level.

4. Color

The concept of mixing several dopants to achieve white emission was discussed. It was concluded that using two dopants to create the appropriate color is an easier proposition than trying to adjust the concentration of three dopants. Of concern, however, are the emission spectra of the dopants as a consequence of the requirement to attain a white emission with the appropriate color rendition. In this regard, there was much discussion concerning the importance of how the white color is attained. For example, the same CIE coordinates can be achieved by mixing two, three or more spectra. However, even though the CIE coordinates could be the same in all three cases, it still does not indicate the same color rendition. Clearly, finding the optimum spectra to mix to give the appropriate CIE and color rendition is important. *No problems were envisioned with obtaining the appropriate spectra because of the infinite variations available for organic small molecules.* (A point was raised, however, that if phosphorescent emitters are required, there have been no blue emitters identified yet).

> This again clearly indicates that a significant materials research is needed to identify both singlet and triplet emitters with sufficient stability and the right emission spectra.

In general it was felt that obtaining the white color with high rendition is achievable with no major roadblock, provided that significant research is carried out to support this activity.

It was not clear, however, which materials system, polymeric OLED or small-molecular OLED, has a better chance of succeeding in providing the "best" white color. The polymeric systems, which are attractive from the device simplicity point of view, are hampered by the lack of polymer design activity. The state of the art materials are currently being developed only in industrial labs and are almost without exception variations of polyfluorenes and polyphenylenevinylenes. Other classes such as, for example, polymers containing aromatic amine groups (polyvinylcarbazole and the like) have not yet been explored. Both industrial and academic laboratories are lagging in terms of materials development.

5. Cost

Establishing a manufacturing platform or process flow would impact the light emitter development work and, obviously, the time to market. It is a misconception that technology development and manufacturing process development are separate issues

that should be addressed sequentially or by different groups. A two-track approach to working on manufacturing issues was proposed.

a) Develop OLED technology that meets the performance specification at acceptable cost. The cost target for near term goals is $\$20/m^2$. It is believed that the present cost for OLED technology is $\$400/m^2$.

b) Perform basic materials development work to simplify and reduce the manufacturing costs. Especially, is there an improved encapsulation technology that can be developed.

Addressing cost, the group emphasized that a factor of 10-20 decrease in cost from the best present day achievable is required to realistically sell OLEDs into the SSL market.

We used the assumption that for lighting, the substrate of choice is light weight/flexible and that the manufacturing platform of choice is a continuous and possible full-up web-based line. (There was a minority of 1 that argued that the production of OLEDs for lighting should remain on flat glass and that this is the only way to drive down cost).

The majority agreed that it is difficult to see a way of meeting the SSL cost requirements without implementing some form of roll-to-roll production including the electrode deposition, encapsulation and any required patterning.

> It is believed that the manufacturing cost could be $50/m2 in 1003 and $20m2 in 2006, under the assumption that the critical issues are being addressed now.

The key issues to address are:

a) organic deposition technology, and

b) encapsulation when the devices are built on web and scaled up to 36" wide web running at 200'/min

6. Inadequate Lighting and Manufacturing Infrastructure

The problem of driving the light fixtures with high currents at low voltages has been raised at several occasions. It was suggested that the major input should and eventually will come from the lighting industry itself and possibly from the national labs such as Lawrence Berkeley National Lab. It was also believed that the dialog with the lighting industry should start soon.

Drive conditions were discussed. Clearly, constant current drive is better for operational stability and for dimming capability, however, there was not enough

information to address the electronic complexities and cost regarding this issue (which is very important).

The concept of a feedback loop to the lamp power controller was discussed. This should not add significantly to the lamp cost and would extend the lifetime and maintain a constant luminance level over the lamp lifetime. With constant luminance, the electrical power will be lowest at the start of life and highest at the end.

Eventually, designers will incorporate the new lighting capabilities into new fixture designs, however, OLED solid state lighting should also be compatible with the existing fluorescent light formats so that these can be easily replaced by OLED fixtures. In other words, existing buildings must be easily retrofitted with OLED lighting.

A segmented lamp, with individually patterned emitters, may be a good format for adjusting the color balance (mood) of the lamp. Also, it may be possible to provide a feedback loop to the power controller to maintain the color balance during lifetime.

> The above conclusions point to inadequate materials as a primary cause of the deficiencies of existing OLEDs.

B. Needed Research Activities

The following shows which material components of OLEDs need substantial improvement:

Substrates

Biaxially oriented polyester needs to be replaced. (Defects, does not allow high temperature deposition, etc.)

Electrode materials

Cathode: Currently used low-work function metals are too reactive and difficult to deposit

Anode: Currently used ITO is too resistive, brittle, difficult to deposit by web coating

Charge Transport Molecules / Polymers

Both polymers and the small molecules are unstable. Very limited selection of emitting polymers to tune white color. Small molecules are difficult to deposit on a large area.

Emitters

Poor luminescence efficiency. Insufficient choice of colors. Unstable.

Singlet emitters: poor life, especially in blue.

Triplet emitters: Very limited selection, insufficient to tune color. Properties unknown

Large Area Processing

Processing and processing equipment must be developed to expand the pro cessing area of OLED devices to achieve high volumes and low cost targets, including:

- Electrode Material deposition
- Polymers and/or small molecule deposition
- Environmental Coatings deposition

C. Cost of Doing OLED Materials Research

At the beginning of the initiative, a large fraction of the funding dollars should go to the materials research. The estimate of the cost of developing a material component is based on the experience with developing a charge transport molecule for organic photoreceptors at Xerox. They funded approximately 50 MY over 3 years to design and develop the material, and the payoff was tremendous. Similar cost was incurred in the design and development of the charge generating material.

Similar time scale, manpower involvement and cost can be expected in the design and development of each materials component for OLEDs.

Given the fact that seven principal material components have to be designed, re-designed and developed, it is not unreasonable to expect that 7 x 40 - 50 MY ~$30 M/y) will have to be spent over the next 5 years or so on OLED materials research to reach the full potential of OLEDs.

Other activities need to be funded as well:

- Web coating and other methods of deposition
- Small molecule deposition
- Encapsulation technology

D. Miscellaneous Observations and Recommendations

There have been many suggestions made at the Workshop how to organize the OLED-for-General-Lighting initiative but no definitive conclusion has been made even in the breakout sessions. The following is a distillation of the statements and conclusions reached in one-on-one conversations with most technical participants and recommendations which generated the most support.

- At this point the U.S. industry has no plans to develop OLEDs for SSL. The reason for this situation is twofold:

    a. The use of OLEDs for general lighting is considered to be far out in the future, too risky at the moment, with so many incremental roadblocks still in the way. The number of inventions to be made makes the detailed business planning virtually impossible and the time horizon is uncertain. All companies involved in the development of OLEDs do so in order to devel-

op OLEDs for displays. Therefore, the existing short-term research and development is *display-oriented*. The prioritization of issues for displays is different from those for general lighting. For example, pixel separation is important while the lifetime of the devices is now not as important. For the general lighting application it is just the opposite.

b. The companies that are involved in the development of OLEDs are mainly startups, or small companies with limited budgets, or small organizations in large companies which have not yet made the commitment to develop OLEDs for general lighting. These companies or organizations cannot afford to invest large sums of money to research and development of technologies that are viewed as being too risky. Particularly, the materials research is costly and time consuming and unaffordable to small companies.

- Without significant government support, none of the U.S. companies will begin to develop OLEDs for general lighting until OLEDs in displays are going to generate revenues. Only an industry / government / academia initiative may change this.
- This is in a nutshell the set of conclusions and views presented at the workshops by a variety of participants. Without exception, all agreed that a properly formulated government sponsored initiative could provide a significant boost to the development of OLEDs for general lighting and assure the US leadership in this field.

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