

*ORGANIC LIGHT EMITTING
DIODES (OLEDs)
FOR GENERAL
ILLUMINATION*

*AN OIDA
TECHNOLOGY
ROADMAP*

An OIDA Report
March 2001

Co-Sponsored by
DOE/BTS

Compiled by
Dr. Milan Stolka

OIDA Member Use Only

OIDA

OPTOELECTRONICS INDUSTRY
DEVELOPMENT ASSOCIATION

1133 Connecticut Avenue, NW
Suite 600

Washington, DC 20036

Ph: (202) 785-4426

Fax: (202) 785-4428

Web: <http://www.OIDA.org>

© 2001 OIDA

Optoelectronics Industry Development Association

All data contained in this report is proprietary to OIDA and may not be distributed in either original or reproduced form to anyone outside the client's internal organization within 5 years of the report date without prior written permission of the Optoelectronics Industry Development Association.

Published by:

Optoelectronics Industry Development Association

1133 Connecticut Avenue NW, Suite 600

Washington, DC 20036

Phone: (202) 785-4426

Fax: (202) 785-4428

Internet: <http://www.oida.org>

Compiled by:

Dr. Milan Stolka

14 Park Circle

Fairport, NY 14450

Phone: (716) 223-5309

Fax: (413) 826-0259

E-mail: mstolka@rochester.rr.com

PART I

**OIDA Technology Roadmap on
Organic Light Emitting Diodes
in Solid State Lighting**

Table of Contents

Part 1: OIDA Technology Roadmap on Organic Light Emitting Diodes in Solid State Lighting

Executive Summary	1
1 Introduction	3
1.1. Background	3
1.2. Materials Systems	5
1.3. White Light	5
1.4. Critical Issues	5
1.5. Cost Comparison and Projections	7
1.6. The Roadmapping Process	8
2 OLED Technologies and Markets	9
2.1. Survey of Applications and Key Performance Attributes	9
3 Technical Challenges and Technology Roadmap	15
3.1. Technical Issues	15
3.2. Manufacturing Issues	44
3.3. Needed Research Activities	49
4 Performance and Cost Goals	55
4.1. Performance Goals	55
4.2. Cost Goals	56
5 References	57
6 Glossary of Terms	58
7 Acknowledgement	59

Part 2. Conclusions and Recommendations

1 Introduction	63
2 Requirements for making OLEDs the Technology of Choice for SSL	65
3 Long-Term Research and Development Issues	67
4 Current Status of OLEDs	69
5 Goals and Milestones	73
Appendix I: Workshop Agenda	75
Appendix II: Workshop Attendees	77

Executive Summary

In view of the diminishing non-renewable resources of energy and the US dependence on oil-producing nations it is imperative that the society takes a closer look at the areas where too much energy is used and find and develop alternatives which use substantially less energy. One of such areas where affluent societies such as ours consume and waste energy is general lighting. In 1998, about 6 Quads (quadrillion British Thermal Units - BTUs) was consumed just to provide lighting to commercial and residential buildings in the USA (1). This level of consumption, which is steadily increasing due to the raising affluence of our society, is simply not sustainable.

It is now accepted that there is a need to develop viable methodologies to conserve up to 50% of the electric lighting load by the year 2010. This can be achieved only partly by energy conservation, advanced electronic controls and more efficient lighting fixtures. The main enabler of the energy conservation effort will be new types of lighting technologies such as SSL (Solid State Lighting), specifically LEDs (Light Emitting Diodes) and OLEDs (Organic Light Emitting Diodes).

- SSL have the promise of providing better, more efficient and more versatile light sources, and at the same time
- contribute to the reduction of energy consumption,
- positively affect the greenhouse effect by reducing the emission of CO₂
- creating new industry and new jobs.

For the most part, LEDs will displace point sources such as incandescent lamps (light-bulbs), while OLEDs will displace area sources such as fluorescent lamps. OLEDs will also create new lighting possibilities by enabling large area illumination sources, panels, ceilings, walls, partitions, fabrics etc. OLEDs have all the attributes to effectively compete with fluorescent lighting, because OLEDs:

- will be more energy efficient,
- will be cheaper to operate,
- will generate white light with high CRI (Color Rendition Index),
- will enable “designer color”, on demand,
- will provide new architectural design opportunities.

There are still many technical obstacles that have to be overcome before OLEDs become a viable alternative to fluorescent lighting. It has been the intent of OIDA to develop a technology roadmap for OLEDs which would identify the critical roadblocks and suggest pathways for overcoming those roadblock. The OIDA roadmapping effort culminated in the OIDA and the Department of Energy sponsored OLED workshop which was held on Nov. 30 and Dec. 1, 2000 in Berkeley, CA and which was attended by the key technical experts on OLEDs in the USA.

The workshop had several objectives:

- To reach an industry consensus on the application of OLEDs in Solid State Lighting,
- To enumerate the technologies that need to be developed to support this application,
- To identify long term research issues,
- To identify and examine major technical problems and roadblocks standing in the way for OLEDs to become a technology of choice for general lighting and provide the basis for developing a technology roadmap to achieve this ambitious goal.

The conclusions of the workshop, the technical status of OLEDs, the description of the main roadblocks, and recommendations are included in this report.

It is the opinion of the OLED workshop participants that *no fundamental* obstacles exist that would prevent OLEDs from achieving the goal of becoming the commercial source of light in residential and commercial buildings.

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 be made 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 and stable materials. **The lack of commercially available high performance materials is the major obstacle** in achieving the goal.

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 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 and 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 in this area could be assured.

1 Introduction

1.1 Background

In the USA, which is by far the largest consumer of energy of all nations, about 38% of all consumed energy (36.3 of nearly 95 Quads) is used in commercial and residential buildings, and 17% of that (6 Quads) is used just for lighting. If, for example, the consumption of electric energy used for lighting is reduced by 50%, the savings to the society would amount to approximately \$10B per year (1). In addition to the fiscal impact, the environmental benefits of reducing the water and air pollution would be significant.

Not much progress has been made in the energy efficiency of the conventional sources of light, incandescent, fluorescent and halogen, within the past 30 - 50 years. At present, about 70% of energy used by these sources is wasted as heat. Therefore, new lighting technologies are desirable and necessary.

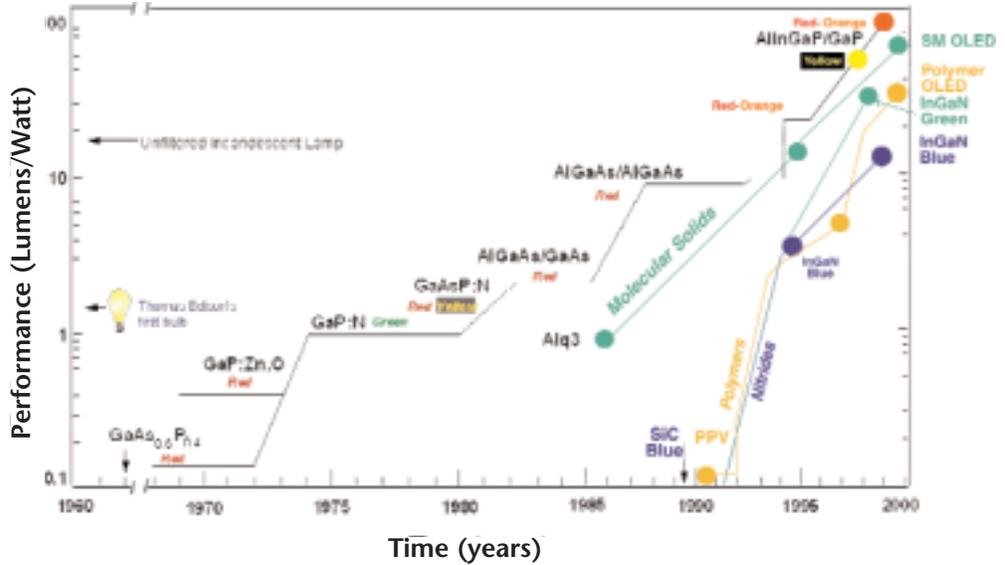
New technologies emerged within the past two decades which have the potential of becoming the main sources of light for general lighting applications: Inorganic Light Emitting Diodes (LEDs) and Organic Light Emitting Diodes (OLEDs)

Solid state lighting (SSL) which includes OLEDs is a major paradigm shift in the lighting industry, which may lead to substantial savings of energy and, consequently, better pollution control. It will require a new lighting infrastructure but it also has a potential for major job creation.

The OLED technology has some very attractive features that are likely to give it prominent place in the lighting market of the future. OLEDs first attracted the attention of researchers in the 1960s because of their potentially high quantum efficiency of fluorescence and the ability to generate a wide variety of colors. Unfortunately, their high operating voltages (>1000V) prohibited them from becoming practical devices. In 1987 however, after Tang and Van Slyke (2) devised a heterostructure double layered device that combined a low operating voltage (<10V) with good brightness (>1000 cd/m²) and respectable luminous efficiency (1.5 lm/W), research regained its momentum. In 1990 electroluminescence from conjugated polymers was discovered by Burroughes et al. (3). Since then, OLED research has achieved, in terms of device efficiency at low current levels, as much as inorganic LED research has achieved in thirty years. Figure 1 shows the evolution of optimum device conversion efficiencies for LEDs and OLEDs. The data points in this figure are not normalized to the same operating conditions (voltages and currents), and therefore, this picture refers only to efficiency and not to the total light output. It shows, however, that the progress in development is rapid.

OLEDs have already achieved emission in all colors of the spectrum — including white. Fine-tuning to any desired color can be achieved by selecting an appropriate emitter or a mixture of emitters with the right emission spectra. Organic chemistry provides virtually unlimited opportunities in designing the desired color.

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



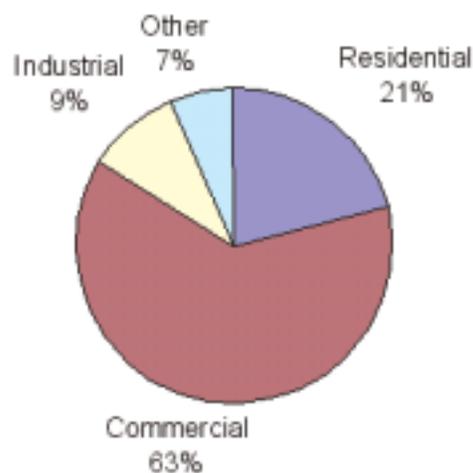
Presently, the main effort in the development of OLEDs is for the full color flat panel display applications. There is also growing interest in using OLEDs as photovoltaic diodes, lasers and now, as the device efficiencies have improved, also as general illumination sources.

OLEDs will be distributed (large area) sources of light. In principle, OLEDs have the potential of being the sources of light in every lighting application except those which require or prefer point source, such as street lighting, search lights etc.

Currently, the major consumer of lighting energy is the commercial sector, followed by the residential usage, industry, commercial outdoors and other (see Fig. 2)

As light sources, fluorescent lamps are favored by commercial and industrial users (Fig.3) because of the higher conversion efficiency and lower overall cost relative to other sources. Due to the distributed nature of light, OLEDs could potentially compete with or eventually displace fluorescent lamps in most applications where the distributed lighting is acceptable or even desirable.

FIGURE 2
Estimated
Distribution of
Lighting Energy
Use Across
Building Sectors
(1)



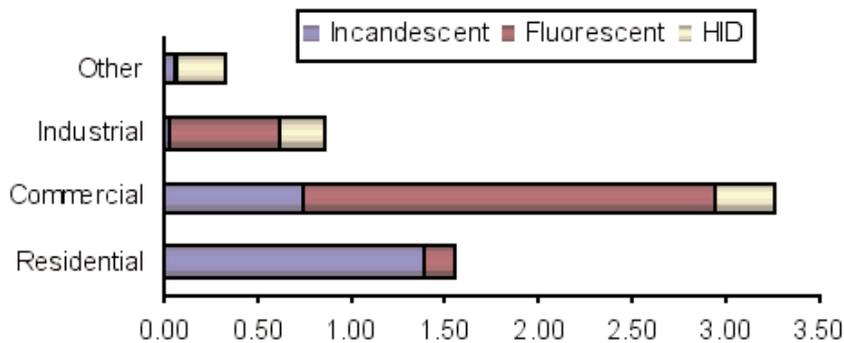


FIGURE 3
Primary energy consumption by sector (1)

1.2 Materials systems

OLEDs are thin film devices where the active charge transport and light emitting materials are sandwiched between two thin film electrodes, one of which being transparent to light. When a voltage bias is applied across the device, electrons are injected from the negatively biased electrode into the active material and simultaneously, holes are injected from the opposite, positive electrode. The injected charges migrate to the recombination zone by the action of an electric field. The charges then recombine. The recombination results in excitation of the emitter and this excitation energy is released as photons. The level of excitation and, consequently, the emitted color is controlled by the chemical nature of the emitter. Organic chemistry offers an inexhaustible variety of structures and thus the choices of emitters and emission colors are virtually unlimited. The materials that emit light can be conjugated polymers or various small molecules. In some cases, the charge transport polymers or small molecules themselves assume the role of an emitter, in other cases, emitters are added either as a separate layer or mixed with the charge transport materials. The details of the device architecture are described in Section 3.1.1.

1.3 White Light

OLEDs are uniquely suited as sources of white light. The most common method of generating white light is appropriate mixing of emitters of the three basic colors. The details and the other methods are described in Sections 3.1.4. and 3.1.5. It is important to note that the color does not change with the viewing angle.

1.4 Critical Issues

The critical issues concerning OLEDs are:

- efficiency,
- life,
- cost, and
- infrastructure.

In the best cases, but not in the same devices, OLEDs have achieved peak luminous efficiencies as high as >50 lm/W (80 lm/W is rumored at the time of writing), peak brightness greater than the blinding 140,000 cd/m² and operating voltages as low as 2 - 4 V. However, the brighter the devices are, the shorter is their operation life. Peak efficiency, peak brightness and minimum operating voltages of OLEDs are not yet achieved simultaneously. The electric currents are still too high and both the operational lifetime and shelf life are still too short.

With the recent announcement of achieving high conversion efficiency — at least for green color — OLEDs have already gained a respectable place among other lighting technologies, as shown in Table I.

Table I. Comparison of Best Conversion Efficiencies for Different Types of Lighting

Type of lighting	Lighting Conversion Efficiency (Lumens / Watt) Under Optimum Conditions (Driving Voltages, Current)
Incandescent	13 - 17 lm/W
Fluorescent	50 - 100 lm/W (typically 90 lm/W)
HID	50 - 130 lm/W
LED	30 - 50 lm/W
OLED	>50 lm/W (green) – still at unacceptably high currents !

The most important shortcoming of current OLEDs is their short lifetime when operated at high luminances. For most display applications, the currently achieved half lifetime (typically defined as time of operation in which the initial luminance drops to one half) of 20,000 hrs at initial luminance of 120 cd/m² at room temperature appears sufficient. **The OLED experts now agree that for general illumination a minimum of 10,000 hrs is needed, with a 20% max. loss of luminance at 850 cd/m² for white light.** The value of 850 cd/m² is the maximum luminance of a distributed light source that still does not produce undesirable glare. This is the first level target, which has to be reached to assure the competitiveness with fluorescent lighting.

The rated average life of incandescent lamps (typical light bulbs) is only 750 - 2,500 hrs while that of fluorescent lamps is about 20,000 hrs. The luminous efficiency of incandescent sources is typically 13 - 20 lm/W while that of fluorescent lamps is about 90 lm/W. In view of the rate of progress in improving the operational lifetimes and efficiencies of OLEDs in the past, it is safe to assume that the parity with fluorescent lamps will be achieved, at least in the laboratory scale, in two to three years for comparable luminances.

For white light applications it is also essential that all emitters that produce white light age at the same rate under all conditions. This has not been achieved and differential aging is still a critical problem. The issues of operational stability and aging are discussed in Section 3.1.2. and the device efficiency in Section 3.1.3.

1.5 Cost Comparison and Projections

It is clear that any new source of light must be cost – competitive with the existing methods of lighting. However, the direct cost comparison of OLEDs with other lighting technologies is still difficult to make because the infrastructure of power distribution and the cost of producing OLED fixtures have not yet been established (Table II).

It has to be noted that customers do not select light sources on the basis of the life cycle cost alone: For example, screw base fluorescent lamps are only slowly displacing incandescent bulbs despite being one third as expensive over the life cycle: (21 x more in cost, but 13 x more in life, and 72% of the cost of electricity). Also, on the basis of cost per 1000 L-hrs inorganic LEDs are only 30% more expensive than incandescent lamps. However, a 75W incandescent bulb emits 1273 L (75 Watts x 17 lm/W), and 1275 lm would require 46 Watts of electric power for LEDs. To obtain that power, one would need 638 LEDs (46 watt / 0.072 watts per LED) at a cost of \$373. Thus inorganic LEDs actually require a cost factor improvement of about 10 with a simultaneous improvement in efficiency of 10 before they will be truly competitive with incandescent lamps. The OLED technology offers opportunity for low cost distributed lighting, provided that all the demonstrated attributes can be combined in a single structure. (see Table III)

Table II. Cost Comparison of Lighting Technologies (5)

	Incandescent bulb	Fluorescent tube	Fluorescent screw base	LED white	OLED white
Wall Plug Power (Watts)	75	20	20	0.072	0.08-0.18
Cost (\$)	0.65	4.75	12.75	0.60	N/A
Lifetime, hrs	750	10,000	10,000	100,000	>30,000
Peak Efficiency, lm/W	17	60	60	100 (orange)	>50 (green)
Init. cost per (c)	0.05	0.4	1.06	42	N/A
Init. Cost per 1000 lm -hrs (c) *	0.07	0.04	0.11	0.42	N/A
Cost of Electricity per 1000 lm -hrs **	0.71	0.20	0.20	0.60	N/A
Total Cost per 1000 lm -hrs (c)	0.78	0.24	0.31	1.02	N/A

* Calculated using lifetime

** Calculated using \$0.12 per kWhr

*** 0.08 for POLEDs, 0.18 for "Small molecular" devices. Due to rapid progress, these numbers may be already obsolete

Table III. Qualitative Comparison of OLEDs with GaN LEDs (5)

Feature	OLED	GaN
Type of light	Distributed source	Point source
Best demonstrated efficacy	>50 lm/W in green	60 lm/W in green
Best demonstrated life	>10,000hrs @ 100 cd/m ²	>10,000 hrs
Fabrication	Simple Processing	Complex Processing
Packaging:	Flexible. Enables Novel Applications (Wrap-around lighting etc.)	Color mixing must be developed
Cost	Projected: Low	Projected: Moderate

1.6 The Roadmapping Process

The roadmapping process should identify not only the opportunities but also the technical challenges facing OLEDs. These challenges are formidable. In order to effectively compete with fluorescent lighting, the challenges include:

- (1) Efficacy improvement to obtain 120 lm/W for white light for a 1000 lm source
- (2) Cost of manufacturing so as to be competitive with traditional light sources
- (3) Development of new infrastructure including powering of high current-low voltage distributed sources, new industries and technologies that are enabled by attributes of OLED SSL.

The technology roadmap for OLEDs comprises three parts:

Part 1 deals with major technical challenges facing OLEDs such as operational lifetime, device efficiency, shelf life and design of materials such as injecting electrodes, charge transporting polymers and small molecules, stable emitters, etc. These are discussed in Section 3.1.

Part 2. deals with the manufacturing issues. While the roll-to-roll coating would be the most effective method of fabrication, many related issues have to be resolved such as differences in the methods of deposition of different materials and layers, protection against ambients and the availability of substrates. The manufacturing issues are discussed in Section 3.2

Part 3 deals with long-term research problems, which may be best attacked by the National Laboratories and universities in collaboration with the industry. Among the research issues are light extraction, materials design and mechanisms of all the individual steps of the light emission process: charge injection, charge migration, recombination, function of emitters, and also the mechanism of degradation. The research issues are discussed in Section 3.3.

The OIDA technology roadmap was developed jointly by the participants of the Nov. 30 – Dec. 1 2000 OLED workshop.

2 OLED Technologies and Markets

2.1 Survey of Applications

We have only begun to imagine what OLED technology can create in the way of products, applications, job creation and new markets. The technology will not only improve existing methods of illumination but will create entirely new lighting product possibilities.

It is unlikely that OLEDs will penetrate into markets where point sources of light are required. However, OLEDs will create new markets where distributed sources of light can be applied or are even desirable. Currently, 77% of all the energy used for lighting is used in commercial buildings, residential housing and industrial (indoor) plants. Incandescent lights now dominate the residential market, primarily because incandescent lighting is almost natural white and, therefore, it offers near perfect color rendition demanded by the general population. The pleasing near white color emitted by incandescent light is enabled by the high temperature of the filaments. Also, from the consumer point of view, the low “first cost” is attractive; to a typical consumer, the total cost of light is not important. On the other hand, cost conscious commercial establishments use more energy-efficient fluorescent lamps. OLEDs have the potential to make an inroad into both markets.

First, OLEDs will offer an unparalleled capability to tune the output color to virtually any shade or tint the customer may demand, including white with near-perfect color rendition. This feature will attract the “quality conscious” customer, primarily for residential applications.

Second, OLEDs will ultimately be more energy efficient to attract the “cost-conscious” customer, primarily in the commercial applications where fluorescent lighting is now predominant. In both markets OLEDs will offer lower cost of ownership and will offer many other advantages over the existing light sources, such as new fixture design opportunities.

The first application will probably be backlighting — such as for location maps in shopping malls, etc. It is the light weight, thinness, and flexibility that allow different mounting options, which will motivate a shift from the conventional light bulbs.

In traditional lighting, OLEDs will have a difficult time competing for the next 4-7 years. However, in non-traditional applications, OLEDs will have a clear performance edge. Example: Owners of upscale houses are willing to spend more than \$1,000 for a light fixture with < \$20 for bulbs. If OLED “wallpaper” is available for the same cost, with a dimmer and color selector (for mood lighting), it will command a premium price. At \$1,000 for 200 sq. feet of OLED wallpaper (\$5 per sq. ft.) — more

than wallpaper but cheaper than wallpaper + the light fixture. Half of the \$5 will go for installation, which leaves \$2.50 for materials. With the advancement of roll-to-roll coating of the OLED devices, this number is attainable.

It is the light weight, thinness, and flexibility that allow different mounting options, which will motivate a shift from the conventional light bulbs. One can envision commercial buildings be lighted by ceiling or wall panels of OLED materials, by partitions, new types of large area fixtures, etc. etc. The desired luminances will vary according to the application. For example, fixtures designed to replace the existing fluorescent lamps with the same square area will have to have luminances of the order of 2,500 cd/m² but if larger areas are preferred, the desired luminances could be less. If a large portion of the ceiling is covered by a light source, the luminances can be as low as 800 - 850 cd/m². Distributed light source will not produce shadows and glare which is a desirable feature in many applications.

The OLED industry focus is now on the application in displays. Only if commercially successful, the companies that develop displays may focus their effort towards OLEDs for general lighting. The focus on displays to some extent slows down the development of OLEDs for general lighting because the priorities are different. Given these circumstances, it is believed 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 accepted that Japan or Europe would be far ahead of the US and take the leadership role. However, 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.

The key assumptions are:

A government - industry - academia partnership will overcome the existing technological roadblocks, and private resources would then be allocated to finding and selling to customers on a worldwide basis.

-
- 
- The technology development will continue. The pace of development will increase.
 - Working prototype devices will be demonstrated and the level of awareness about OLEDs will grow.
 - The life-cost will compete with other existing sources of light.
-

Existing Applications of OLEDs (No Breakthrough Required)

1. Readily converted to OLED (2000 - 2005)

a. Monochrome applications

- LCD backlights
- Small monochrome displays for hand held electronic devices (cell phones, PDAs, digital cameras)
- Niche applications such as head-mounted displays

b. Two multicolor applications

- Car electronics (radios, GPS displays, maps, warning lights etc.)
- Instrument electronics

c. Full color application

- Small full color displays

2. Near-readily converted to OLED (2005 - 2010)

a. Low flux white

b. Low level backlighting

c. High level backlighting

Existing Applications not Readily Converted to OLEDs (Require Breakthrough).

1. General white applications (to replace incandescent / halogen)

2. General white applications (to replace fluorescent)

New Applications that Could be Enabled by OLEDs

1. Applications benefiting from programmable performance (intensity, color, direction, focus).

2. Applications capitalizing on integration with displays, vehicles, architecture military equipment, etc.

3. Smart lights

Factors Affecting Penetration Into the General Lighting Market

1. Accelerating factors

- Large area coatings. Light source can be shaped to product.
- Any type of substrates from rigid such as metal, plastic, glass, ceramic, etc., to flexible (plastic films, rolls, loops, foils, filaments, fabrics, etc.)
- High power efficiency. In a short period of 10 years the efficiency improved from 1 lm/W to 80 lm/W).
- Unlimited choices of color for different applications and types of lighting.
- Variable pixel size from displays to large areas. No upper limit to pixel size.
- Low voltage of operation.
- Fast switching speed for “intelligent” lighting.
- Light weight.
- Ruggedness, vibration resistance
- Thin film light sources (almost “two dimensional”)
- Allows the use of polarizers.
- Large area (distributed) lighting, low glare
- Low cost of manufacturing.

2. Inhibiting factors — major improvements required

- Short operational and shelf life, stability at high brightness levels
- Differential aging of different colors
- Low device efficiency
- Device complexity
- Uniformity of large area lighting sources
- High electric currents
- Customer response (subjective factors).

3. Impact / Benefits

- Enormous energy savings for society.

- Environmental impact associated with the reduction of the need for electricity (greenhouse effect, air pollution, depletion of non-renewable sources of energy)
- Creation of new lighting (fixture) industry. New methods of power distribution and conduits. New jobs.
- New architectural designs enabled (lower ceilings, contour lighting, wall / ceiling panel lighting, space saving in airplanes, etc.)
- Quality of lighting.

3 Technical Challenges and Technology Roadmap

3.1 Technical Issues

3.1.1 Device Architecture

“Small molecule” OLED devices

Simplicity is the key to achieving low cost of manufacturing. However, current OLED devices are complex. The OLEDs are thin multilayer structures consisting of a substrate, several active materials sandwiched between two electrodes, at least one of which is transparent to light, and a protective barrier layer. Two types of active materials are currently used:

- Light emitting polymers (sometimes labeled as LEPs or POLEDs), and
- “Small molecules” (SM or SMOLEDs).

Even though these groups of materials are functionally identical, the methods of deposition may differ. Polymers are typically deposited by solution coating methods while the “small molecules” are usually vapor-deposited (sublimed).

The architecture of SM devices is illustrated in Fig 4:

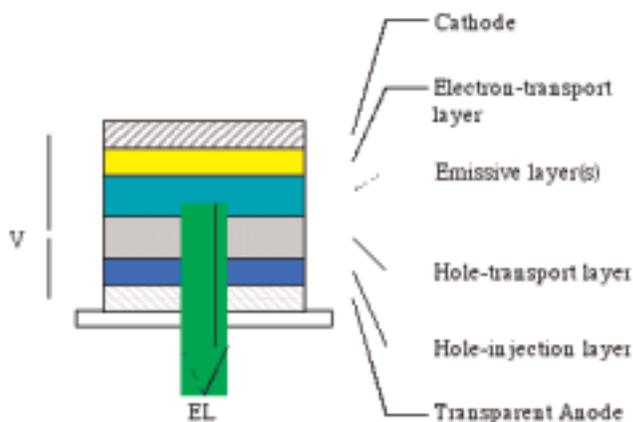


FIGURE 4
Architecture of a typical layered SM OLED device

The number of layers can be reduced if, for example, the emitter compound is mixed with one of the charge transporting layers or if one of the charge transporters also assumes the function of an emitter. Currently, the most efficient and stable devices need an extra layer to protect the components against the ambients, and injection-modulating layer(s) between the electrodes and the charge transport layers. Some devices, which use triplet emitters, may have an additional, exciton barrier layer that trap triplets in the luminescing region.

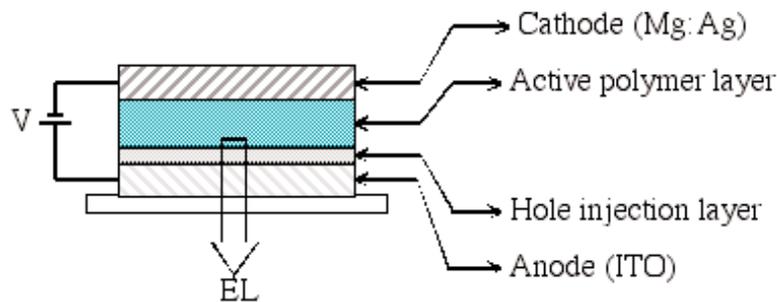
So today's devices may have a total of 7 - 9 layers, some of them deposited by a different technique (sputtering, vapor deposition, solvent coating, etc). The deposition of most layers may require humidity- and oxygen-free conditions and all require class 10 clean room. The cost implication of such complexity is high. The deposition of each layer negatively impacts the cost and the yield of the final device. Ideally, for large - scale continuous roll-to-roll coatings, solution depositions would be preferred but it is not always applicable.

Polymeric OLED devices

The polymeric OLED devices typically have fewer layers as shown in Fig. 5. The electroactive polymers may serve multiple functions: electron and hole transport and emission, even though dopant emitters can be added to tune the color. The active polymers and the hole injection layer may be solution-coatable but the electrodes are again coated by different techniques such as vapor deposition. The architecture of these devices may appear to be more cost effective but again, full scale solution coatings would reduce the cost further.

For OLEDs to penetrate the market it is essential that they be deposited on flexible polymeric substrates. However, the use of plastics may prohibit the application of some deposition methods, especially those requiring high temperatures.

FIGURE 5
Architecture of a typical polymeric OLED device



One important deficiency of the OLED devices is low value of the light extraction coefficient R_e (see Section 3.1). Most of the photons generated in the bulk of the devices are lost due to absorption, reflections and waveguiding in the current types of layered devices. Some proposed solutions may require changes in the device architecture.

There is a need to simplify the device architecture

- the number of layers should be reduced but not to compromise life and performance
 - simple, cost effective deposition processes must be developed
 - significant research in both the materials design and manufacturing technologies is needed to simplify the design of the device and the deposition processes
-

3.1.2 Operational Lifetime vs. Brightness

These two items present special challenges for OLEDs for general lighting: High luminance levels, at least of the order of 850 cd/m^2 with high conversion efficiency and sufficient operational stability (greater than 10,000 hrs of lifetime), must be achieved. Currently, efficiencies are much lower at these levels, for example, 100 cd/m^2 . At present, the OLED community defines “end of life” as the point at which the luminance decays to 50% of the value at $t=0$. This value is then normalized to an initial luminance of 100 cd/m^2 to quote the lifetime value. This may be adequate for comparison purposes in research and development, but not for the general lighting applications. For display applications, for example, the eye is sensitive to a 5% burn-in and similar values are to be expected for distributed panel – like sources of illumination. Also, a customer should not be able to perceive the difference in light intensity and a shade of color between a new and an “aged” panel, if those two are placed next to each other. Therefore, for application to the lighting industry, the definition of lifetime must be well understood before conclusions of the status of OLED technology can be made.

It is generally agreed by the OLED community that the first level target should be 10,000 hrs with a maximum 20% loss of luminance starting at 850 cd/m^2 . It is very difficult to make an industry comparison as the operational conditions and the test environment are not well documented

The lifetime to half brightness is inversely proportional to operating brightness (or current density). Degradation mechanisms leading to the decay of brightness are relatively unstudied. The degradation products from such thin films represent such tiny amounts of material that direct study is conceptually difficult. Specific mechanisms are therefore not agreed upon. There is no single cause that would limit the useful life of the OLED devices. Among the factors that can 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 a common knowledge that devices with small molecules with high glass transition temperature T_g usually live longer than devices employing materials with low T_g , even though the correlation is not always valid. The current empirical goal is materials with T_g in excess of 150 °C.

Conventional green OLEDs using both small molecule and polymeric materials have been reported to have projected lifetimes (to half of the initial brightness) of > 20,000 hours at 100 cd/m², when encapsulated in a glass package filled with dry nitrogen.

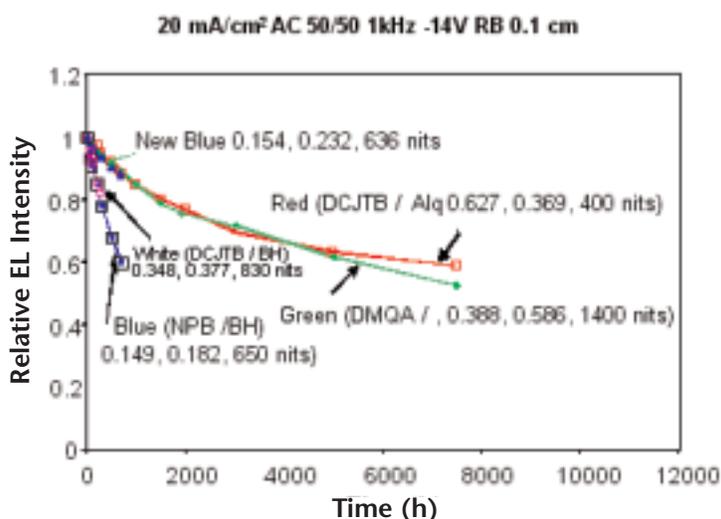
OLED devices with different color emitters typically degrade at different rates, as shown in Table IV and Fig. 6. The green devices are the most stable and the operational lifetime decreases towards both ends of the spectrum. The unequal rates of degradation for different colors could obviously be a problem for designing white light OLEDs.

Table IV. OLED Luminance and Half Life (6)

Color	Red	Green	Blue
L (cd/m ²) @ 20 mA/cm ²	~400	~1500	~600
Half life (hr) @ 20 mA/cm ²	~8000	~7000	~4000
Half life (hr) @ 100 cd/m ²	3×10^4	10^5	2.5×10^4

As the Table IV shows, for applications that require low luminance (100 cd/m²) the life (50% decay) may be already sufficient but at higher luminances (higher current densities), the life is still too short.

FIGURE 6
Operation
Lifetime of a SM
OLED. (6)



However, a substantial improvement of SM OLED stability has been noted recently: White light emitting devices with the initial luminance of 1000 cd/m² (approximately what the lighting industry requires) lose about 25% of the initial luminance in 1000 hrs. Most of the aging occurs within the first hours of operation. If we assume that the operation life time should be >10,000 hrs and the allowed decrease in intensity will be only 20% over the lifetime, an improvement by a factor of at least 15 is needed. Fig. 7 represents the state of the art SM OLEDs with white emission. However, as the accelerated tests indicate, different colors still age with different rates (Fig. 9 for POLEDs).

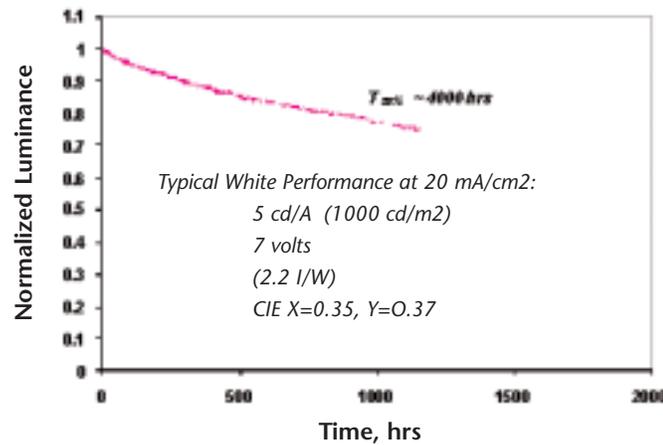


FIGURE 7
Stability of White Light OLED at 20mA/cm² (6)

This is a substantial improvement over the situation of about a year ago when an improvement by a factor of more than 100 was required. Also, the data shown in Fig.8 prove that the emission spectrum does not change, which indicates that the different color emitters age with approximately the same rate, at least within the first 1000 hrs.

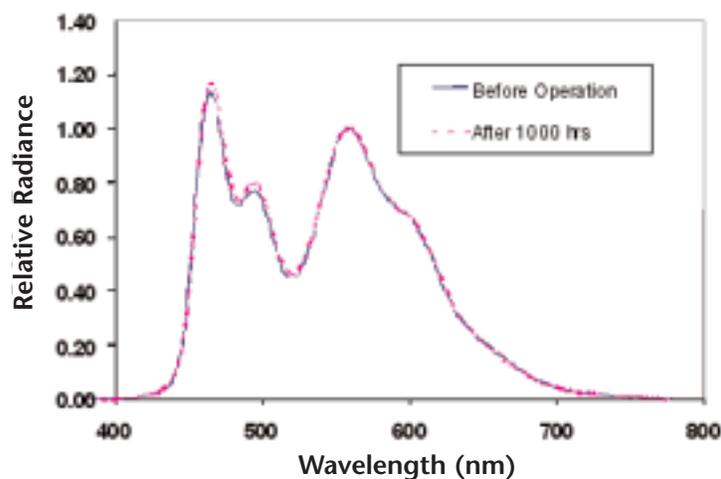
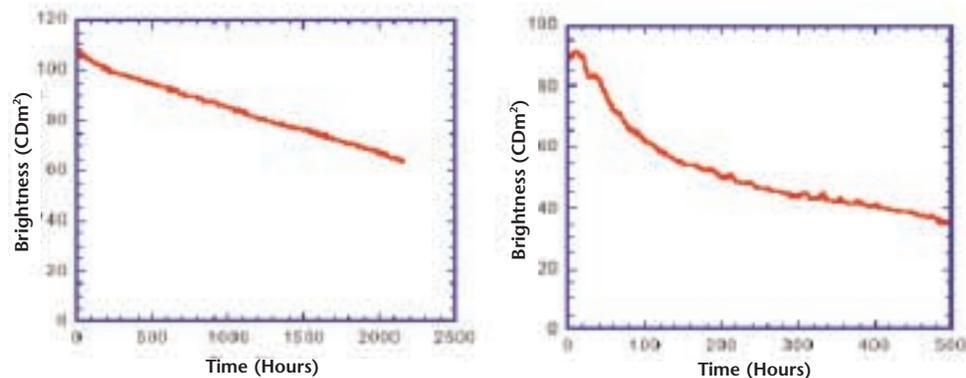


FIGURE 8
White SM OLED Spectra. Operational Stability 1000hrs, 20 mA/cm², init. 980 cd/m² (6)

FIGURE 9

Luminance at of blue and red polymeric OLEDs at 7 mA/cm² in an accelerated test at 70°C. The acceleration factor between 20 and 70°C is about 10 that gives >30,000 hrs at room temperature. As in SM OLEDs, blue decays faster than red, and both decay faster than green. (7)



The ultimate limits to the operating lifetime of OLED devices may be caused by chemical reactions initiated by energetic excitons created by injected charge carriers. Triplet excitons are particularly suspect, due to their long lifetimes in organic materials. The efficient removal of long-lived triplet excited states via rapid recombination on a phosphorescent dopant therefore has the potential to significantly extend the device operating lifetime. Recent reports indicate that the addition of red phosphorescent dopant increase the operational lifetime from about 10,000 hrs to >10⁵ hrs.

The issue of materials *purity* comes to the picture as well, as demonstrated on the example of a conjugated polymer partially contaminated with residual acetylenic triple bonds from the synthesis (see Fig. 10). The “cleaner” polymer with minimum amount of residual triple bonds yields a device with >100 hrs life at 70 °C (extrapolated to 4,000 hrs at 25 °C) while the “contaminated” polymer completely degraded in a few hours.

Other possible causes of degradation of OLEDs are variously attributed to:

- electromigration of cathodes due to localized short circuits,
- photodegradation on the presence of oxygen,
- electrochemical reactions at the interfaces, and
- general instabilities of the molecules in the oxidized (cation-radical) states.

These shortcomings will diminish with the appropriate design of the small molecules or polymers that carry the charges to the recombination sites, composition and treatments of electrodes and development of better encapsulation methods to prevent the access of oxygen and moisture. For small display devices, the lifetimes of all colors (> 5,000 hours at 100 cd/m²) are sufficient. For lighting applications, these lifetimes are grossly inadequate. Therefore, for the application to general lighting an effort must be focused on increasing lifetime for high brightness applications and for large areas.

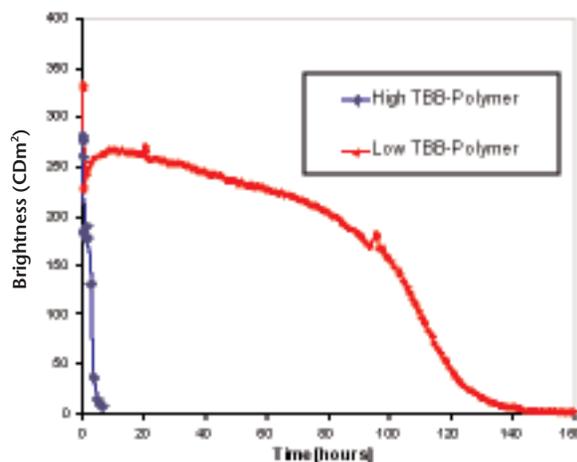


FIGURE 10
 Influence of defects on operation lifetime (by accelerated ageing.)
 TBB is a symbol for acetylenic bonds
 Accelerated ageing — about 40 times room temperature (8)

Understanding of the following issues must be acquired to improve the operation life of OLEDs:

- The degradation mechanism
- The role of triplet excitons in the degradation processes
- The effect of Tg and morphology of the active materials
- The role of structural impurities in active polymers in polymeric OLEDs

This will lead to the design and development of more stable materials.

3.1.3 Efficiency

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, some of the detailed processes leading to the creation of photons are inefficient. These processes are:

- charge injection, i.e the charge balance factor γ (a fraction of injected charges that produce excitons),
- the singlet excitation efficiency η_s (the fraction of excitons that are formed as singlets), and
- the quantum efficiency of fluorescence Φ_f .

Therefore, the internal device efficiency η_{int} is a product of these three factors:

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

Charge balance factor γ

The charge balance factor can approach unity if hole injection is balanced with electron injection by an appropriate choice of injecting electrodes and charge transporting materials. Unequal injection rates may 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. However, the existing electrode materials are unacceptable for OLEDs for lighting. They are either too resistive, too brittle, too reactive, or too light absorbing. Similarly, the charge transport materials that also affect the charge injection balance, are also subject to degradation. All these materials will be eventually replaced and the charge injection balance will have to be established again.

Singlet excitation efficiency η_s

Based on spin statistics, the singlet excitation efficiency η_s 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 which were believed to be useless in generating light. Until recently, this was thought to impose a 25% fundamental limit on the internal quantum efficiency of *electroluminescence*.

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 of singlet excitation efficiency could be, but values close to unity could be contemplated and are viewed as possible in the future.

Furthermore, also recently, experiments showed that triplets could be harvested as well by adding heavy-metal containing phosphorescing dopants, as photon emitting species. Phosphorescing dopants containing heavy metals (Pt, Ir, Au etc.) proved to be useable in selected cases, raising the internal quantum efficiency to >62% (!) - at low current densities (2×10^{-3} mA/cm²), 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 quantum efficiencies to much higher values.

Even though the harvesting of triplets is a relatively new phenomenon, some of the latest (green) devices operated at low current densities (0.1 mA/cm²) show the internal efficiency hint in excess of 62% (!) and the external device efficiency η_{ext} of 15.4%. (See Fig. 11). At the current densities of the order of 10 mA/cm² when the luminances are near the desired 850 cd/m², the external efficiency η_{ext} is near 10% which is only a factor of 3-4 less than needed for the application in general lighting. It has to be noted, that these devices still did not utilize the recent advances in improving the light extraction efficiency.

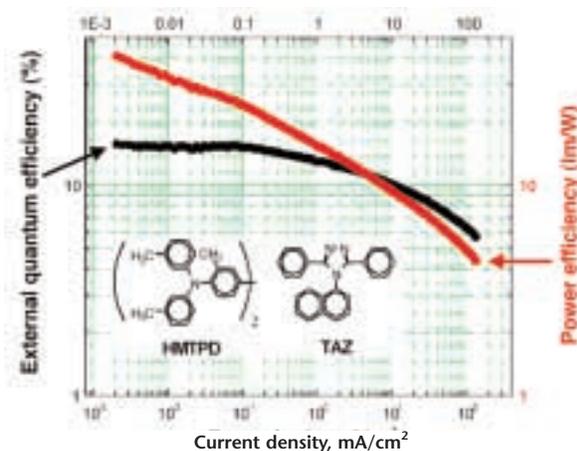


FIGURE 11
External quantum efficiency and power efficiency of a triplet – emitting device with an iridium complex. The structure of the device was ITO/HMTPD/7%-Ir(ppy)₃:TAZ/BCP/Alq/AlLi (9).

These discoveries that the population of singlets can be higher than 25% and that triplets can be also harvested prove that the internal quantum efficiency of OLED devices) can be close to unity (!). Only future research will tell if the most efficient devices will be all singlet or all triplet emitting devices or perhaps a combination of both.

The quantum efficiency of fluorescence Φ_f can also approach unity but only in dilute solutions. General problem is to maintain high Φ_f in solid state. Few materials have Φ_f greater than 50% in OLEDs. Sometimes, greater luminescence efficiency in small-molecular devices is achieved by adding dopants, for example quinacridone to the host Alq₃. Again, further progress can be expected in raising the efficiency of fluorescence.

Other causes of poor Φ_f are 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 rate (Fig. 12). The optimum spacing between the emissive zone and the cathode – determined in a model experiment using SiO₂ 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.

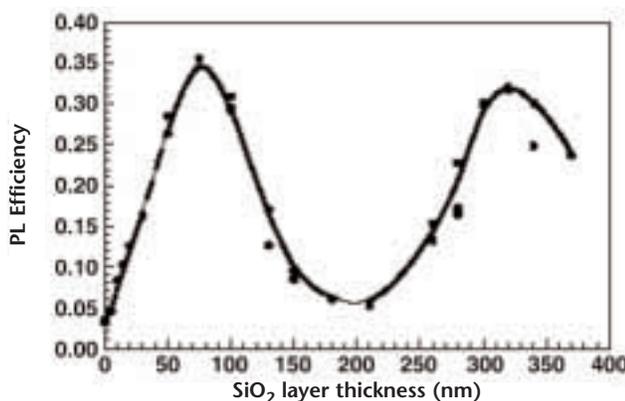


FIGURE 12
Photoluminescence efficiency vs. distance between the emission zone and mirror electrode (10)

Light Extraction Coefficient R_e

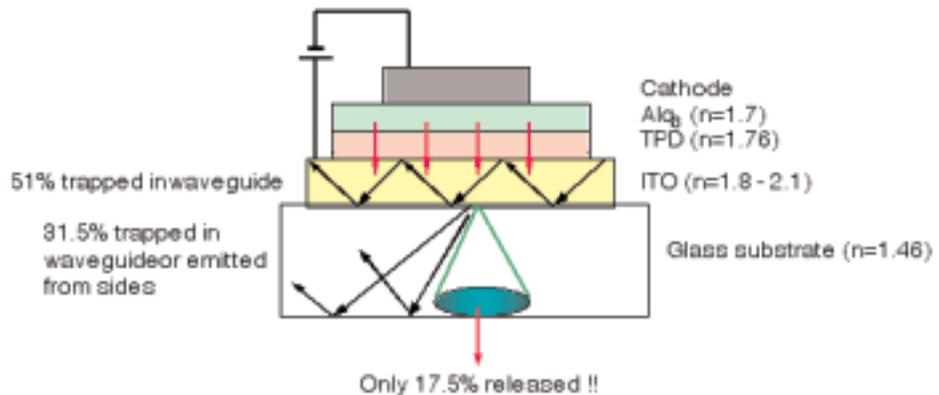
Due to internal losses, only a fraction of generated photons makes it out of the device. The external efficiency η_{ext} is related to the internal efficiency by a formula

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

where R_e is the extraction coefficient which represents the number of photons emitted to the exterior of OLEDs per number of photons generated inside the device. Poor light extraction was the single most important factor limiting the external efficiency of OLED devices. The internal reflection of photons caused by high refractive indices of the layer materials is the main cause of poor extraction efficiency. Over 80% of the light can be lost to internal absorption and waveguiding in a simple planar device. For example, according to a recent publication, a typical Alq₃ and TPD based OLED releases only 17.5 % of photons generated inside the device. (See Fig. 13). R_e is a function of the refractive indices of the medium in which the photons are generated and of the adjacent layers such as glass or plastic substrate or air.

FIGURE 13

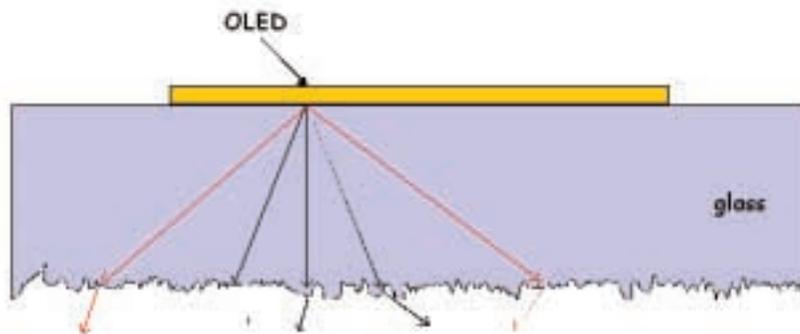
A scheme illustrating the losses of photons due to internal reflections and waveguiding in layered OLED devices



Several ways have been shown how to improve the extraction efficiency of the device. One of them is surface texturing, such as illustrated in Fig 14. Surface texturing gives the photons multiple opportunities to reflect and find the escape cone. Even though the surface texturing experiments have begun only recently, a factor of 2 - 3 improvement in R_e has already been achieved.

FIGURE 14

Surface texturing will reduce waveguiding and internal reflection (11)



Another technique is a substrate modification by index-matching fluid as illustrated in Fig. 15. Again, an improvement by a factor of 2.5 has already been achieved.

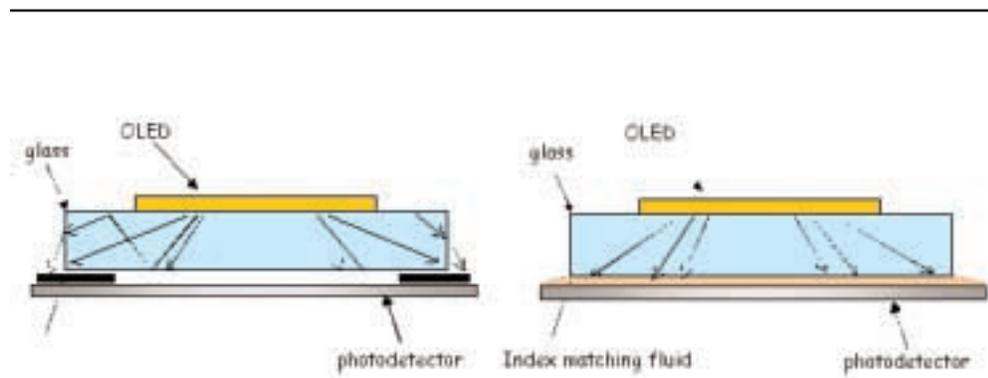


FIGURE 15
Substrate modification with index matching fluids also reduces internal reflections. (12)

Other techniques have been suggested and will be explored. These include substrate modification by laminating lens arrays (basically a controlled surface texturing) (13), where an improvement of R_e by a factor of 2 has been achieved, an addition of an ordered layer of silica microspheres (14), etc

It is now believed that exploration and application of these methods will gradually increase the extraction efficiency to about 80% within the next 5 years.

The following Table V summarizes the current status and projection of the external quantum efficiency of OLEDs for 2006, five years from now, provided that the government / industry / academia collaboration is established and effective. These numbers show that OLED can meet the requirements of the lighting industry for the device efficiency. It has to be emphasized that these projections are conservative and take into consideration only the existing inventions and recent breakthroughs. The progress can be accelerated and greater efficiencies achieved if the critical materials research effort is substantially increased.

Table V. Current status and projections of internal and external efficiencies of OLED devices

	2001			2006 Projection		
	η_{int}	R_e	η_{ext}	η_{int}	R_e	η_{ext}
Polymeric OLEDs	14 %	45	6.3 %	28	80	22%
SM OLEDs - singlet emission	15 %	30	5.0 %	18	80	14 %
SM OLEDs - triplet emission*	62 %	30	18.5 %	84	80	67 %

Ref. (6).

η_{int} Internal quantum efficiency

R_e Extraction coefficient

η_{ext} External quantum efficiency

* At low current densities. Mixing emitters to produce white light was not reported at the time of writing

All these values (for example those in the line SM OLED - triplet emission) have not been achieved in the same devices, and the high efficiencies were achieved at low current densities, below what is required to achieve the desired luminances.

Similarly, the following Table VI describes the efficiencies obtained in CDT on POLEDs for different colors. The data clearly show that the luminances obtained at reasonably low current densities are still inadequate, especially at the edges of the visible spectrum.

Table VI. Efficiencies of POLED devices

Color		Deep blue	Blue	Green	Orange	Red
CIE-x		0.162	0.180	0.379	0.612	0.674
CIE-y		0.099	0.240	0.581	0.385	0.324
Maximum Cd/A		1.90	4.09	14.9	3.5	1.20
Max.lm/W	lm/W	1.32	3.47	17.5	4.6	1.82
	V	4.40	3.60	2.60	2.4	2.4
	cd/m ²	570	156	29	105	30
	mA/cm ²	30.834	3.93	0.2002	2.9882	2.1597
@20mA/cm ²	lm/W	1.29	2.95	7.30	3.4	1.30
	cd/A	1.70	2.35	9.50	3.3	1.5
	cd/m ²	340	860	1900	650	300
	V	4.13	4.53	4.07	3.0	3.50
@3.5V	lm/W	0.77	3.41	10.6	2.8	1.30
	cd/A	0.90	2.14	11.6	3.2	1.5
	cd/m ²	56	123	830	1200	300
	mA/cm ²	6.24	3.18	7.17	38	20

(Ref. 15)

Another common way of defining the efficiency of the light emitting device is to express it as luminous efficiency, Lumens per inputted watt energy (lm/W). The reported peak luminous efficiency in the green portion of the spectrum of an OLED device is 60 lm/W (80 lm/W is rumored). However, in the red and blue, the demonstrated peak efficiencies are still way below that, of the order of 5 lm/W, but these numbers are changing rapidly.

White light spectrum requirements for general illumination are determined by the desired color rendition index CRI and luminous efficacy (lumens per watt - lm/W). Many spectral solutions exist to achieve good quality white, both broad and narrow band. Optimal solutions with acceptable white light have luminous efficacy ranging from 300 to 400 lm/W.

The optimal SSL source with 100% electrical to optical power conversion efficiency would have an efficacy of approximately 350 lm/W. To achieve the minimum need-

ed 120 lm/W the SSL source must have an electrical to optical power efficiency (electrons to photons) of about 34%.

For example, the current status and projections for luminous efficiency of white and green OLEDs generated in Eastman Kodak Labs (ref) are shown in Table VII.

Table VII. Luminous efficiencies of current and future OLED devices (6)

	Luminance (cd/m ²)	Current Density (mA/cm ²)	Voltage	Efficiency (lm/W)	Estimate for 4 x 2 ft Light Fixture:		
					Luminous Output (lm)	Total Current (A)	Input Power (W)
White Now	1000	20	7	2.2	2335	149	1041
Future White	1000	2	3.5	44.9	2335	15	52
Green now	1167	2.5	5.5	27			

This Table shows that a 20 - 50 x improvement in white efficiency is needed to equal fluorescent lights. However, the luminance requirement for future lighting application is only 850 (cd/m²) and the size of the fixtures can be larger than 4x2 ft. In addition, the latest advancements in using high-efficiency phosphorescent (triplet) dopants for generating white light and in photon extraction have not been applied here.

▼

Essential research and development activities needed to remove the roadblocks to achieving high OLED device efficiency:

- Charge injection: reduce the injection barriers
 - Balanced charge injection: match the work functions of electrodes with oxidation potentials or electron affinities of the charge transport materials
 - Photoluminescence efficiency: understanding and search for new triplet emitters
 - Phosphorescence efficiency: understanding and search for new phosphorescing additives
 - Light extraction: change the device architecture to minimize internal absorption, reflection and waveguiding
-

3.1.4 Color Issues of White-Light OLEDs

Introduction (16)

For white-light OLEDs to be used for general lighting, they should have appropriate white color and good color rendering performance for illuminated objects. Color rendering, as well as energy efficiency (efficacy), have been the two most important criteria for traditional light sources for general lighting. U.S. Energy Policy Act (EPACT 1992) specifies the minimum color rendering indices (explained below) as well as the minimum efficacy of common lamps.

Color rendering is determined solely from the spectrum of the source. Thus, the spectra of white-light OLEDs need to be designed to meet requirements in both aspects. Color rendering is best achieved by broadband spectra distributed throughout the visible region, while the efficacy is best achieved by a monochromatic radiation at 555 nm (green) where the human eye response reaches its maximum. Thus color rendering and efficacy are the two properties in trade-off. For example, a low -pressure sodium lamp (having a light orange color, used in some highways and parking lots) has an efficacy of about 200 lm/W, the highest among available discharge lamps, but no colors of objects are shown. A red car (or any other colors) in a parking lot looks gray. On the other hand, a xenon arc lamp, having a very similar spectrum as day light and exhibit excellent color rendering, has an efficacy of only about 30 lm/W.

▼

When color rendering is calculated, however, it has been found that two-emitter OLEDs are unlikely to achieve acceptable color rendering properties.

An advantage of OLEDs is that they are available in almost any wavelength in the visible region, and the spectrum design of white-light OLEDs will be more flexible than for traditional discharge lamps where the available spectra depends on available phosphors and emissions from gas. In the case of multiple-emitter white-light OLEDs, white light can be achieved by mixture of two or more OLEDs of different peak wavelengths. Three-emitter (or more) white-light OLEDs are expected to provide good color rendering that can be used for general lighting. The evaluation method for color rendering of light sources is well-established by CIE (Commission Internationale d'Éclairage = International Commission on Illumination), and the color rendering index is widely used in lighting industry for many years since 1965. Below, some fundamentals of the CIE colorimetry system including the color rendering index is described, and applications to the design of white-light OLEDs are discussed. Chromaticity Coordinates and Color Temperature White LEDs, or any other light sources for general lighting, should have a white color in order to show all the colors of illuminated objects appropriately.

Color of light is expressed by the CIE colorimetry system. The spectrum of given light is weighted by standardized three spectral functions as shown in Fig. 16. From the resultant three weighted integral values, called tristimulus values X, Y, Z, the chro-

maticity coordinate x, y is calculated by $x = X / (X+Y+Z)$, $y = Y / (X+Y+Z)$. Any color of light can be expressed by the chromaticity coordinate x, y on the CIE 1931 (x, y) chromaticity diagram, as shown in Fig. 17. The chromaticity diagram, shows more detail.

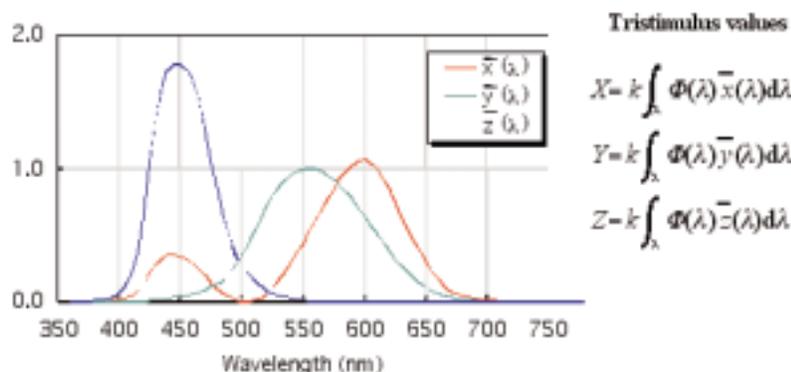


FIGURE 16
CIE 1931 XYZ
color matching
functions (16)

The boundaries of this horseshoe-shaped diagram are the plots of monochromatic light, called the spectrum locus. Also plotted near the center of the diagram is the so-called Planckian locus, which is the trace of the chromaticity coordinate of a blackbody at its temperature from 1000 K to 20000 K. The colors on the Planckian locus, given in the blackbody temperature, are described as color temperature. The colors around the Planckian locus from about 2500 to 20000 K can be regarded as white, 2500 K being reddish white and 20000 K being bluish white. The point labeled “Illuminant A” is the typical color of an incandescent lamp, and “Illuminant D65” the typical color of day light, as standardized by the CIE.

The colors of most of traditional lamps for general lighting fall in the region between these two points, 2850 to 6500 K. The color shift along the Planckian locus (warm to cool) is generously accepted or purposely varied for general lighting for preferred atmosphere, while color shift away from the Planckian locus (greenish or purplish) is hardly acceptable. As an example, Fig. 18 shows the chromaticity coordinates of 23 common fluorescent lamps.

Strictly speaking, color temperature cannot be used for colors off from Planckian locus, in which case what is called correlated color temperature (CCT) is used. CCT is the temperature of the blackbody whose perceived color most resembles that of the light source in question. Due to the nonlinearity of the x, y diagram, the iso-CCT lines are not perpendicular to the Planckian locus on the x, y diagram as shown in Fig. 18. To calculate CCT, therefore, another improved chromaticity diagram is used, where the iso-CCT lines are perpendicular to the Planckian locus by definition.

FIGURE 17
CIE 1931 (x, y)
chromaticity
diagram (16)

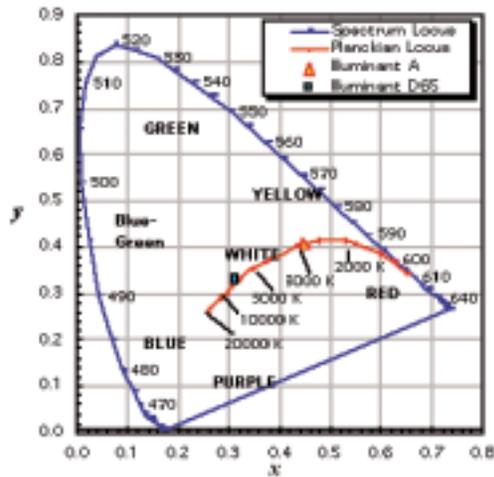
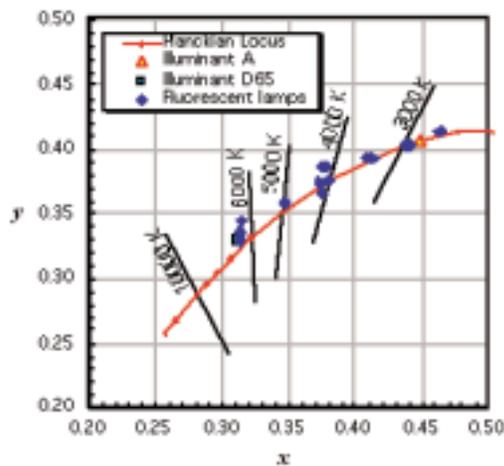


FIGURE 18
Chromaticity
coordinates of 23
common fluores-
cent lamps. (16)



An important characteristic of the chromaticity diagram is that light stimuli on the diagram is additive. A mixture of two colors will produce a chromaticity coordinate falling on the line between the chromaticity coordinates of the two colors. Figure 19 shows an example of mixing two colors of OLED, each at 485 nm (blue) and 583 nm (orange) with a half-bandwidth of 20 nm. The mixture of these two colors having the same optical power will produce white color at about 4000 K and is shown in Fig. 19 as a diamond. But, note that, even though the color of this mixed light looks white on white paper, the color rendering is unacceptable (see next section) and is not usable as a light source for general lighting where green and purple would look gray.

Color Rendering

The Color Rendering Index (CRI) of a light source is evaluated by comparing the appearance of various object colors under illumination by the given light source with that under reference illumination, day light for CCT > 5000 K and Planckian radiation for CCT < 5000 K. The smaller the color differences of the object colors are the better the color rendering is. The y standardized method, the color rendering index (CRI), is defined by the CIE and has been in wide use in lighting industry for many years. In this method, 14 Munsell samples of various different colors, including a few very saturated colors, were carefully selected.

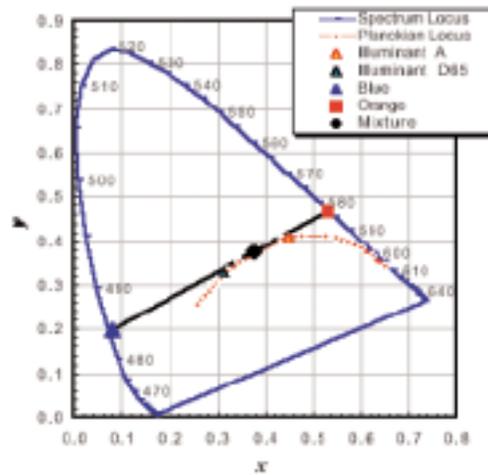


FIGURE 19
Mixture of two colors on the (x, y) chromaticity diagram (16)

The color differences, denoted as ΔE_i , of these color samples under the test illumination and under the reference illumination are calculated on the 1964 $W^*U^*V^*$ uniform color space. The process incorporates corrections for chromatic adaptation. Then the Special Color Rendering Index R_i for each color sample is calculated by $R_i = 100 - 4.6 \Delta E_i$. This value gives an indication of color rendering for each particular color. The General Color Rendering Index, R_a , is given as the average of the first eight color samples (medium saturation). With the maximum value being 100, R_a gives a scale that matches well with the visual impression of color rendering of illuminated scenes.

For example, lamps having R_a values greater than 80 may be considered high quality and suitable for interior lighting, and R_a greater than 95 may be suitable for visual inspection purposes. Thus, the spectral distribution of white-light LEDs should be designed to achieve the R_a value required for aimed applications. For comparison with conventional light sources, the CRI (R_a values) of several common types of fluorescent lamps and HID (High Intensity Discharge) lamps are shown in Table VIII.

Luminous Efficacy

The energy efficiency of light sources involves 1) efficiency of conversion from electrical power (W) to optical power (radiant flux in watts), and 2) conversion from radiant flux (W) to luminous flux (lumen = lm), which is a theoretical value determined by the spectral distribution of light, and is called luminous efficacy of radiation, K , (units lm/W). The luminous efficacy of monochromatic radiation $K(\lambda)$ at wavelength λ , is shown in Fig. 3.5, and is given by

$$K(\lambda) = K_m \times V(\lambda)$$

where $K_m = 683 \text{ lm/W}$, $V(\lambda)$ is the spectral luminous efficiency (of photopic vision) defined by CIE and is the basis of photometric units. K_m is a constant given in the definition of the candela, and is called maximum luminous efficacy of radiation. No light source can exceed this value of efficacy — as shown in Fig. 20. Note that the $K(\lambda)$ peaks at 555 nm, and falls off at both ends of the visible region. The values of $K(\lambda)$ can be interpreted as the theoretical limit of luminous efficacy at each wavelength. For example monochromatic light at 450 nm has luminous efficacy of only

26 lm/W (theoretical limit). For real light sources including OLEDs, the luminous efficacy of radiation is calculated from its spectral power distribution $S(\lambda)$ by

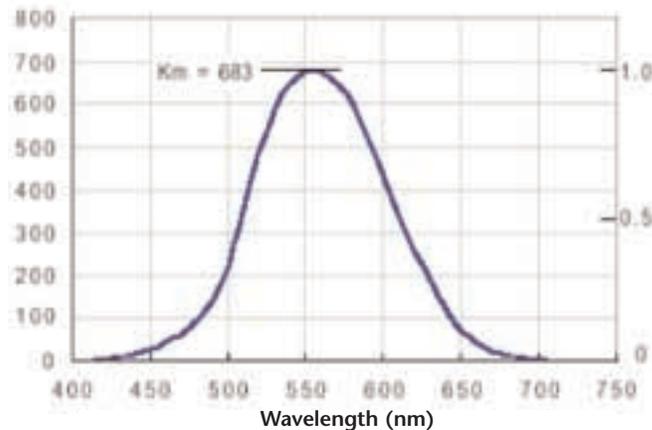
$$K \text{ [lm/W]} = \frac{K_m \int S(\lambda) V(\lambda) d\lambda}{\int S(\lambda) d\lambda} \quad \text{where } K_m = 683 \text{ [lm/W]}$$

Table VIII. General CRI of Common Lamps (16)

	CCT	R _a		CCT	R _a
Daylight	6430	76	Metal halide	4220	67
Cool white	4230	64	Metal halide, coated	3800	70
White	3450	57	Mercury, clear	6410	18
Warm white	2940	51	Mercury, coated	3600	49
Cool white deluxe	4080	89	High pressure sodium	2100	24
Warm white deluxe	2940	73	Xenon	5920	94

The spectral power distribution of white-light OLEDs should be designed to have high luminous efficacy. For comparison, the total efficacy (lumens per electrical power including ballast losses) of traditional light sources is summarized in Fig. 21. Within a lamp type, the higher-wattage sources are generally more efficient than the lower-wattage sources. High-pressure sodium, metal halide, and fluorescent lamps are the most efficient white light sources.

FIGURE 20
Luminous efficacy of monochromatic radiation, $K(l)$ (16)



Application to White OLED design

From the information given above, when the spectral power distribution of a light source is given, one can calculate chromaticity coordinate, CCT, CRI, and the luminous efficacy of radiation. A case of a three-emitter white-light OLED is described here for an example. The same white color can be created from numerous combinations of different R,G,B spectra.

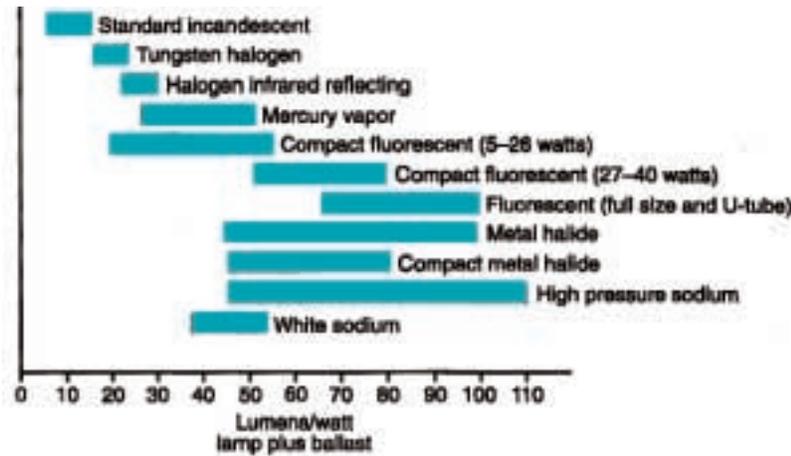
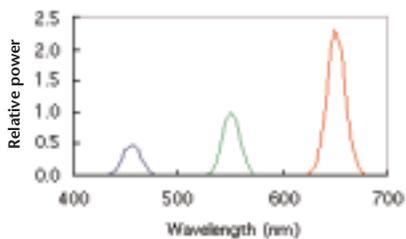


FIGURE 21
Efficacy of traditional light sources (16)

Figure 22 shows the results of a simulation of three OLEDs at peak wavelengths of 450, 550, and 650 nm, with their relative power adjusted to create white color of 4000 K. Each OLED is a model using a Gaussian function, with half-bandwidth of 20 nm. In this case, CRI (R_a) is only 37 with luminous efficacy of 228 lm/W (theoretical maximum). An $R_a = 37$ is not acceptable for use in general lighting, except for limited outdoor use.



x	0.3792
y	0.3736
CCT[K]	4011
Δ_{uv}	0.001
R_a	37
Efficacy [lm/W]	228

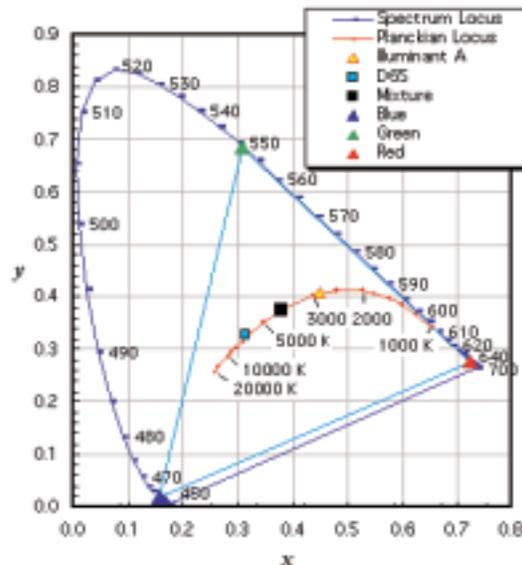


FIGURE 22
Simulation of a three-emitter white light OLED (poor example) (16)

Figure 23 shows the result of simulation of another combination, with peak wavelengths of 459.7, 542.4, and 607.3 nm. With this combination, $R_a = 80$ with luminous efficacy of 400 lm/W (theoretical maximum) is achieved. If the efficiency of the OLED emitters is 20%, the total efficacy would be 80 lm/W, comparable to typical fluorescent lamps. $R_a = 80$ is well acceptable for general lighting including indoor applications. This is only a demonstration, and is not necessarily the best result. There may be other combinations with even better results. As shown by this, the selection of wavelengths makes big differences in performance of white-light OLEDs. In real cases, as the efficiency of OLEDs differ at different wavelengths, selection of wavelengths is restricted. Using more sophisticated simulation analyses with restrictions applied, optimum designs of white-light OLEDs using available color OLEDs for any desired CCTs can be made. Using four emitters should give even better color rendering than three emitters.

FIGURE 23
Simulation of a three-emitter white light OLED (good example) (16)

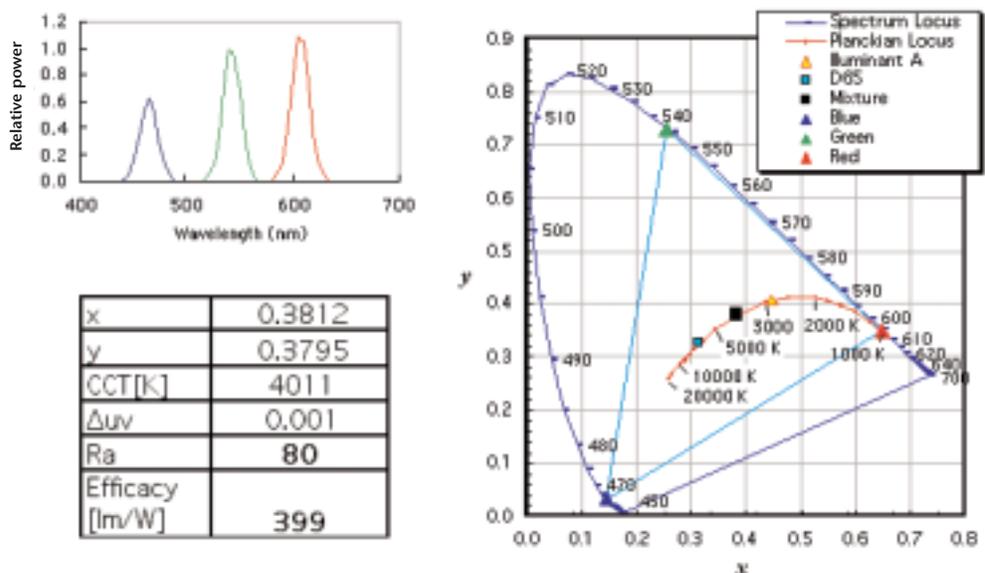


Figure 23 shows the result of simulation of another combination, with peak wavelengths of 459.7, 542.4, and 607.3 nm. With this combination, $R_a = 80$ with luminous efficacy of 400 lm/W (theoretical maximum) is achieved. If the efficiency of the OLED emitters were 20%, the total efficacy would be 80 lm/W, comparable to typical fluorescent lamps. $R_a = 80$ is well acceptable for general lighting including indoor applications. This is only a demonstration, and is not necessarily the best result. There may be other combinations with even better results. As shown by this, the selection of wavelengths makes big differences in performance of white-light OLEDs. In real cases, as the efficiency of OLEDs differ at different wavelengths, selection of wavelengths is restricted. Using more sophisticated simulation analyses with restrictions applied, optimum designs of white-light OLEDs using available color OLEDs for any desired CCTs can be made. Using four emitters should give even better color rendering than three emitters.

The CRI (R_a) of the two-emitter OLED shown in Fig. 19 is only about 4. Two-emitter white-light OLEDs in any wavelength combinations can never produce R_a value acceptable for general lighting.

The definitions of the terms in photometry and colorimetry used in this section follow that found in “International Lighting Vocabulary,” CIE 17.4 / IEC 50 (845) – 1987. For further details of colorimetry, an overview of the CIE system of colorimetry is available in an article by Y. Ohno, “CIE Fundamentals for Color Measurements,” Proceedings, IS&T NIP16 International Conference on Digital Printing Technologies, Oct. 15-20, 2000, Vancouver, Canada.

3.1.5 Color Design

Both small-molecular and polymeric systems with *singlet* emitters have achieved full color with good positions on the CIE diagrams (see Figs. 24 for “small molecular” devices and Fig. 25 for polymeric OLEDs) but improvements are still required. For example, saturated blue emitters are still not adequate.

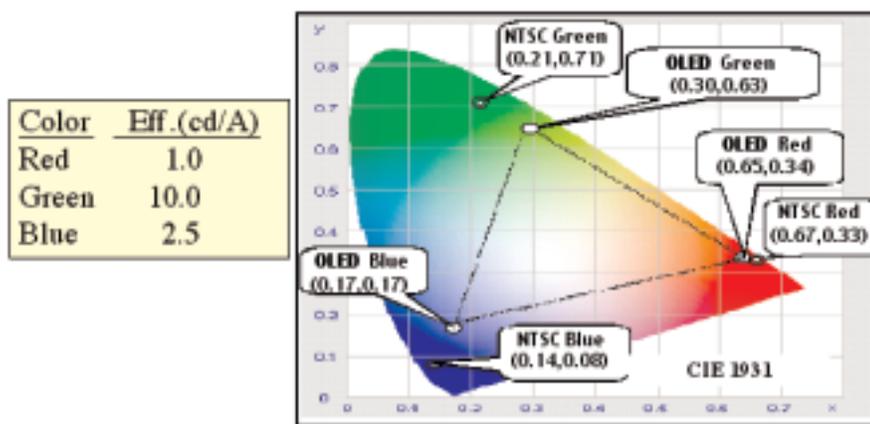


FIGURE 24
A chromaticity diagram of one of the latest SM devices. (6)

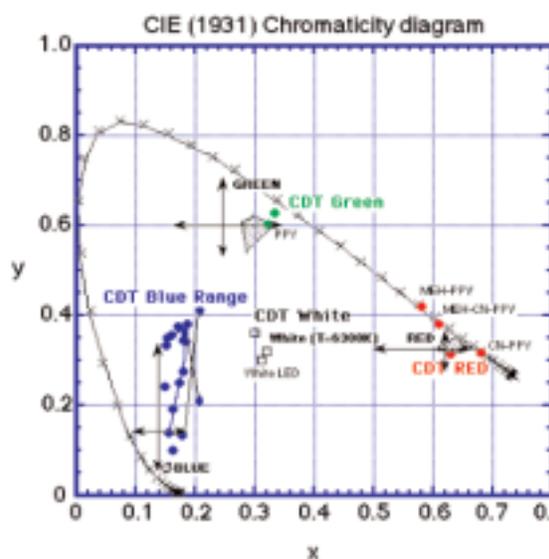
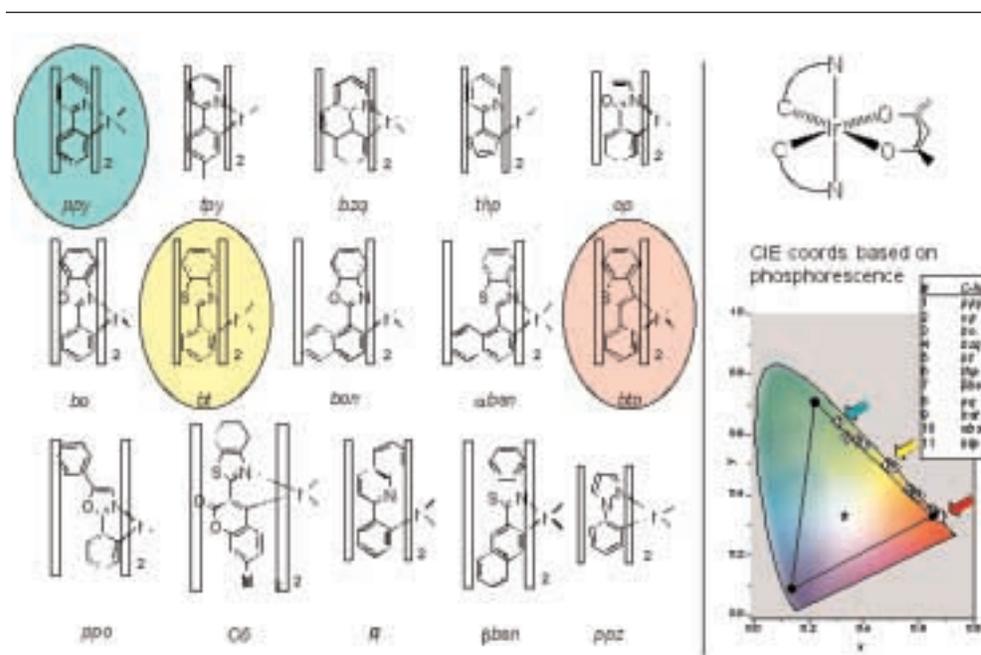


FIGURE 25
Chromaticity diagram of polymeric OLEDs (7)

The tone of color in polymeric OLEDs where the polymers themselves act as emitters is varied by modifications in the polymer structure. Even though progress has been made in designing polymers which emit in some of the key positions of the chromaticity diagram (Fig. 25), more synthetic effort is needed to develop an inventory of polymers which emit in other colors and to improve the saturation of existing colors.

The recent progress in harvesting triplet states, which lead to increased efficiencies also lead to a greater selection of colors, as Figures 26 and 27 show. For example, a group of newly synthesized iridium complexes produced colors shown in Fig. 25

FIGURE 25
An example of color selection by using iridium based complexes as triplet emitters (9)



Another example in Fig. 26 shows that platinum complexes can move the emission color to another position in the chromaticity diagram. At the time of writing, the blue triplet emitter was still missing.

White color (an equivalent to $T=6300K$) is within the reach of both polymeric and small-molecular OLEDs but achieving *stable* white color still is not. With the right mix of existing emitters or through minor changes in the structure of light emitting polymers these coordinates can be met. Therefore, getting white emitted light does not require a breakthrough. The progress in improving the quality of white light will be evolutionary. As stated before, the emitters or emitting polymers that yield the white do not have the desired operational stability.

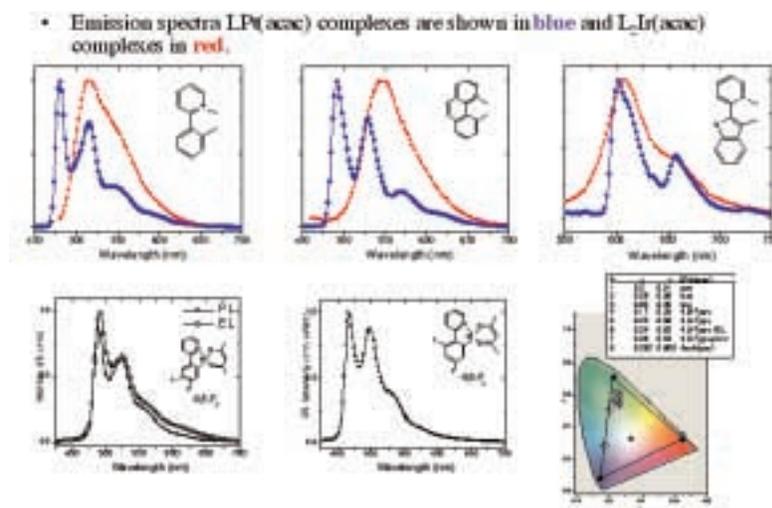


FIGURE 26
Colors generated by platinum based triplet emitters. (9)

Four basic methods to achieve white light are well known:

- obtain a broad emission spectrum (white light) from a single material (“white” dopants, blends or copolymers etc.),
- vertically stack R,G,B emitters using transparent pixels or layers,
- mix in three different dyes (emitters) to approximate white,
- use organix or inorganic phosphor down-converters.

All methods have been demonstrated but none of them produces stable white. The third method offers specific advantages since the color mix CRI index can be tuned in situ. Specifics will depend on the materials. The colors obtained by using singlet emitters in SM OLED devices are presented in Table IX.

Table IX. Performance of Color SM OLEDs (6)

	Blue	Green	Red	High Eff. Blue	White
Host	Blue Alq	Alq	Alq		
Dopant	Perylene	Coumarin	DCJTB		DCJTB
L (nit)*	355	1980	430	795	836
Eff. (cd/A)*	1.8	10.0	2.15	4.0	4.2
CIE _x	0.163	0.263	0.617	0.149	0.388
CIE _y	0.194	0.619	0.377	0.182	0.337
Half-life (hrs)*	~1,200	~5,000	~7,000	~1,000	~1,000

*20 mA/cm² current drive; 8-10 V

Again, given the rapid development, these numbers may be already obsolete.

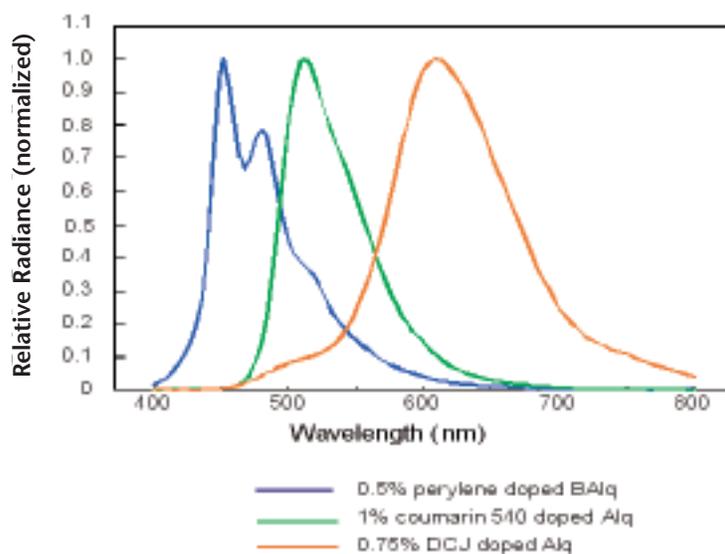
An example of generating white light by mixing emitters is shown in Table X and Figure 27.

Table X. White Light Produced by Mixing Emitters in SM OLEDs (6)

	Blue	Green	Red	Resulting White
CIE Coordinates	0.16, 0.15	0.29, 0.63	0.677, 0.33	0.27, 0.35
OLED Color Wavelength	454 nm	520 nm	454 nm	

Average Color T = 8413 over 27 - 512 cd/m²

FIGURE 27
Spectra of colors making the white SM OLED, 20 mA / cm². (6)



Both polymeric and SM OLEDs have broader emission spectra than CRTs, which makes it easier to fine tune the final “white”, i.e. getting the right CIE point, than with traditional sources of white light (Fig. 28).

It has to be emphasized, however, that getting the right CIE point may not necessarily produce a good “white” for general lighting applications. The definition of “good” white light (the desired CIE coordinates) has yet to be developed on the basis of customer requirements for different applications.

The concept of mixing several dopants to achieve white emission is now generally accepted. It was clearly 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.

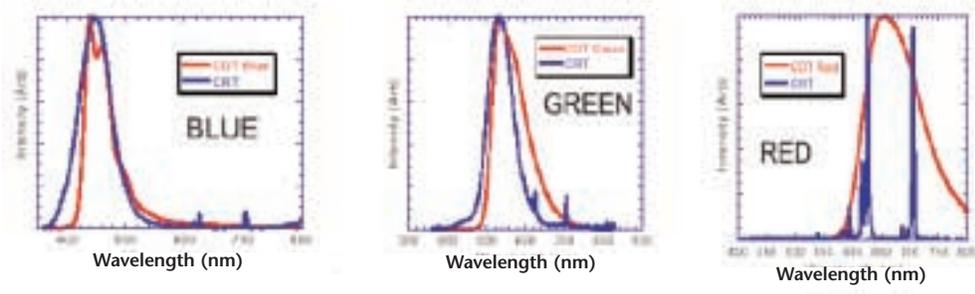


FIGURE 28
Comparison of spectra of polymeric OLEDs with CRT colors (7)

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.*

One encouraging finding is that increasing the luminance by increasing the voltage and, consequently, by increasing the power consumption, changes only little the color temperature (see Fig. 29).

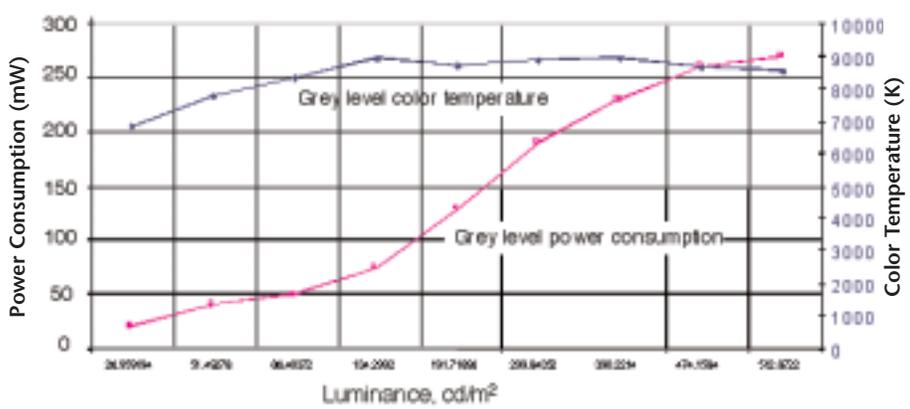


FIGURE 29
Grey level color temperature and grey level power consumption vs. luminance (6)

- Quality white light appears to be within reach of both SM and polymeric OLEDs.
- The definition of “acceptable” white for general lighting application has yet to be developed.
- The operational life of white light emitting devices is unacceptably short and has to be improved by many orders of magnitude before the introduction to the market can be considered.

3.1.6 Shelf Life, Environmental Stability

Of importance is not only the operational lifetime of the OLED device but also the shelf life under adverse conditions. It is now well understood that the devices must be protected against the access of moisture and oxygen. With good encapsulation using an epoxied lid, lifetime is limited by diffusion of moisture through the epoxy seal. At high temperatures, thermal expansion near the T_g destroys devices at about that point, although excursions above T_g for a limited time may be survivable if the device is not operating. Systematic temperature-dependent work on small molecule materials is still missing.

Presently, the community utilizes epoxy sealing with an oxygen and moisture trap inside of the package. A lot of development work is on going to develop monolithic encapsulations to improve the durability for high temperature and humidity conditions. Another factor for environmental durability is the materials themselves. The hole-transporting layer is typically the weakest link at elevated temperatures. In the small molecule field, a number of researchers are reporting on high T_g materials development.

Another example that clearly supports the need for extensive materials research is the accelerated shelf life test of SM OLED with two different hole transport molecules, everything else being equal (Fig. 30.) The performance of a device with NPB SM severely decays after several hours at elevated temperatures, while the device with Spiro-TAD is unchanged even after exposure to 140°C:

Progress in designing stable systems has largely been empirical. Significant research is needed to obtain the understanding of all the causes of OLED decay including the effect of structural features. This has to include the development of analytical tools, particularly from selected disciplines in electrochemistry, photochemistry, and photophysics.

The impact of handling large currents is not understood. Major changes will have to be made in the lighting infrastructure to incorporate OLEDs.

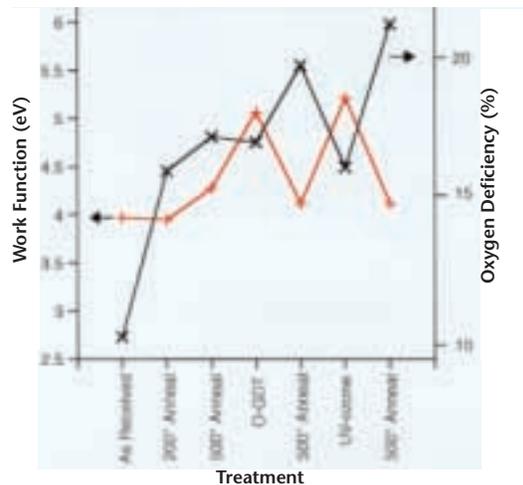
3.1.8 Electrodes

In order to get the light out of an OLED, one of the electrodes must be transparent. Today, indium-tin oxide (ITO) is used as the transparent anode. Currently used substrates with the ITO layer have about 85% transmission. ITO-coated plastics, as received, have work function too low, about 2.7 eV but the value can be modified, for example, by annealing at different temperatures, to match the HOMO level of the hole transport material. For efficient injection of holes into the hole transport material, the work function of the anode must be high. As Figure 31 shows, this can be achieved by annealing the ITO-coated substrate, but if the base material is plastic, there is a limit to which the temperature can be raised:

ITO is currently the only practical hole-injecting electrode but is generally coated with more controlled injection layer. For “small molecular” OLED devices, phthalocyanines and porphyrins are typically used. These materials can be vacuum deposited. For polymeric devices, there is increased use of conducting polymers on ITO, such as polythiophene doped with polystyrene sulfonic acid.

ITO on plastic substrates is commercially available. However, the current cost of coated substrates is prohibitive, of the order of \$200 per m². ITO is brittle and easily cracked and damaged. Large scale web coating may reduce the cost of deposition, but ITO on plastic will not be a viable transparent anode material in high through-put roll-to-roll process (the stresses will be too large). In addition to that, the conductivity of the ITO layers is lower than needed, by about one or two orders of magnitude, particularly for large area distributed devices. The resistivity of the conductive layer

FIGURE 31
Annealing can change the oxygen content and the work function of ITO (18)



should be $<50\text{W sq}$, particularly for large areas. **Alternative conductive materials must be developed.**

Conducting polymer electrodes may offer a potential solution. Polymer LEDs have been demonstrated using conducting polymers as anodes. There are several known candidates (e.g. polyaniline, polyethylenedioxythiophene and polypyrrole). Sufficient transparency in the visible has been demonstrated. However, the conductivities of these materials in the form of optical quality thin films is nearly two orders of magnitude too low for the lighting applications (typical values currently available for conducting polymer films are in the range of a few hundred S/cm). This must be increased by nearly two orders of magnitude if we are to use metallic polymers as the transparent anode in OLEDs for lighting. Some of this can be made up by using thicker films (surface resistance is then the only parameter).

Unfortunately, thicker films tend to reduce transparency. This, too, can be improved. Oriented films are an opportunity. Orientation and the resulting improved structural order will lead to higher conductivity and to lower absorption (at least in the perpendicular polarization). Routes to oriented films of conducting polymer include self-assembly through the use of liquid crystalline materials (liquid crystalline conjugated polymers are known; liquid crystalline side chains can be used to induce order and orientation). The achievement of optical quality films of high conductivity metallic polymers is a major opportunity and a difficult problem requiring a combination of synthesis and materials science.

Current cathode materials are limited to low work function metals, such as Ca, Li, Mg or their alloys (Mg/Ag, Al/Li). These cathodes are extremely reactive and require protection against moisture and oxygen. Large-scale coatings would be especially cumbersome and expensive. Some progress is being made in this area: for example, thin ($<5\text{ nm}$) layers of LiF, CsF and Li_2O , vapor deposited onto the active molecules, prior to deposition of metal such as aluminum, have been successfully used as cathodes. Both anode and cathode materials are inadequate for OLEDs.

-
- 
- There is a need for transparent anodes with conductivities greater than ITO
 - Cathode metals are too reactive. Unconventional approaches are needed or alternatives have to be found
-

3.2 Manufacturing Issues

3.2.1 Synthesis of Materials. Purity.

Large-scale syntheses of most device components are largely untried. One problem is that with 100 nm films used for OLEDs and efficient deposition technology, only 10^{-7} g of material is used per m^2 . 1 kg would coat 10^{10} m^2 of OLED. Even allowing for a factor of 10 or so for deposition inefficiencies, this hardly represents a lucrative market for the chemical companies and, consequently, no investment into the design of new more efficient OLED materials can be expected from the suppliers. It appears that either makers of OLED devices themselves, in cooperation with universities, have to fund this research, or the funding should be found within the framework of the government / industry / academia cooperation.

Purity has not been properly addressed. Most users assume that train or gradient sublimation increases purity to required levels. This may not always be the case. Furthermore, there are no applicable techniques for determination of purity to the required levels. With organic molecules, small concentrations of impurities or molecular fragments may not be detectable by conventional techniques, and may still give the correct elemental analysis, but the trace impurities may be highly damaging. Conversely, impurities, which are damaging to inorganic semiconductors may be benign to organics.

Manufacturing of all the chemicals used in small-molecule OLEDs is straightforward. All syntheses are done within 1-3 steps, mostly with high yield and short reaction time, without sub-zero temperature steps, and all can be carried out without vacuum techniques. Purification is easy, mostly with column chromatography, which implies convenient scale-up. Recrystallization and/or sublimation are also employed. The former is the best for industrial scale. However, for materials that are not very soluble or not very stable in solution, sublimation is more suitable.

Polymeric materials are more difficult to synthesize and purify. Once an impurity is built into the polymer structure it cannot be removed except by a chemical treatment or a thermal conversion, where available. Any such treatment should be done without affecting the primary function of the polymer and the treatments are never 100% effective.

Organic purity level is usually defined by mass spectroscopy, liquid chromatography analysis, etc. However, the experience with organic photoreceptor materials suggests that these techniques may not be sensitive enough to detect the critical impurities. Some impurities are benign but some may have to be reduced to below ppb (parts per billion) levels, mostly undetectable by existing analytical techniques.

-
- ▼
- Small amounts of active materials now used in OLEDs do not provide an incentive for suppliers to carry out research and development. Academic institutions may have to take the early responsibility.
 - Conventional analytical tools may not be sensitive enough to detect critical impurities
-

3.2.2 Large-Area Coating and Depositions

On a lab scale, thermal evaporation and spin coating are used to build SM and polymeric OLED prototypes, respectively. These approaches are not good for low cost, large area manufacturing. Roll-to-roll solution coatings appear to be the technology of choice. The roll coating technology for OLEDs can borrow from the experience with large area high speed web coatings of organic photoreceptors where the demands on coating uniformity and defect-free nature of the product are similar to those for OLEDs. The photoreceptor devices are also multilayer structures where individual layers are coated from different solvents. Many secondary properties of active materials must be controlled: viscosity of solutions, adhesion, wetting, no gelation at low or high temperatures, resistance to shear stresses, solvents etc. etc.

Deposition of some materials such as electrodes may still require vacuum. It is highly inconvenient for roll-to-roll manufacturing. Conventional vacuum deposition can be used, but capital cost and materials wastage increase in quadrature with size. For high throughput, new ideas utilizing roll-coating on flexible substrates are needed.

3.2.3. Uniformity

Due to space charge limited conduction in most OLEDs, voltage variation scale with the third power of thickness, so uniformity is particularly important or current will sink through thin areas. If charge traps are present in the materials due to the impurities, as has been demonstrated in many OLEDs, the thickness dependence becomes even higher.

No specifications for the device uniformity have been developed for lighting applications. Presently in the small-molecule technology it is thought that 5% thickness uniformity is adequate.

-
- ▼
- If continuous web coating is used to fabricate OLEDs for general lighting, much can be learned from the photoreceptor manufacturing technology for laser printing industry. The high-speed web coatings with tolerances and uniformities that approximate the needs of OLEDs are well established.
-

3.2.4 Protection From the Ambients, Packaging

At present, the low work function cathodes used in OLEDs are reactive and must be protected from water vapor and oxygen. The metal-polymer interface is the weak-link; degradation of this interface will limit the lifetime. More generally, OLED operation involves excited states of the molecules or macromolecules involved in the emission. When in such excited states, the molecules or macromolecules are highly susceptible to oxidation (photo-oxidation is well known). Thus, packaging that would hermetically seal the devices will be required.

Since the permeability of plastics to oxygen and water vapor is orders of magnitude too high, novel barrier films will be required. Inorganic layers (or laminates of inorganic and organic layers) can provide sufficient barrier properties. However, such inorganic layers must be pinhole free and they must be robust. Brittle barrier layers would not withstand the flexing and stretching involved in a roll-to-roll process.

Barrier films with sufficiently low permeability are not currently available. The barrier properties must be sufficient to give extended lifetime even when used at elevated temperatures since the high brightness needed for emission will generate heat (the higher the EL efficiency the less the heat). The availability of flexible plastic substrates with sufficiently good barrier properties is essential to the lighting application. The required tolerances are unknown. State of the art packaging involves gluing a lid of either glass or metal onto the display using UV-cured epoxy. Oxide desiccant is often incorporated in the package. This probably functions to absorb water from the epoxy curing or from photoresist in situ shadow masks. The epoxied lid technique is limited to devices of a few inches diagonal, and is completely ineffective for flexible devices. New packaging technology is therefore required for large area SSL. Candidate technologies generally apply some variant of organic/inorganic hybrid thin film encapsulation.

For large area low cost manufacturing by web processing there are approaches such as lamination etc. that are on-going.



- In the absence of alternatives for cathode metals, new highly effective barrier methods will have to be developed that would prevent the access of moisture and oxygen.



3.2.5. Transparent Substrates

Even though glass substrates are used at the present, OLEDs for general lighting will have plastic substrates, which will provide the needed flexibility and conformability, will have lower weight and thickness, and will enable roll-to-roll coating. Glass is fragile. Plastic is highly desirable for lightweight, rugged, conformable or flexible applications. **No suitable plastic substrate is currently available.** Polyethylene tereph-

thalate (PET) is widely used as the best available compromise but T_g is too low (~70°C). Heat stabilization does not change this but reduces shrinkage up to the stabilization temperature, usually 120 °C. Quality control on rolls of PET is appallingly bad by thin film standards. Spikes of >1000Å, long edges (non-uniform stretch), scratches, bubbles, needles of crystals of foreign material and other inclusions are plentiful. Lack of good quality substrate is seriously impeding the development of plastic OLEDs. The substrates must have high chemical resistance to common coating solvents, scratch resistance, low oxygen permeability — below 10⁻⁵ cc.m².day.atm and low water permeability (<1µg/ m².day).

Higher T_g substrates under development include polyethersulphone and polynorbornene, the latter of which suffers from poor mechanical strength. All are expensive and available only in limited quantities. Transparent conductor is an integral part of transparent substrate for OLED applications. Low speed of deposition, low conductivity and patternability are all issues here.

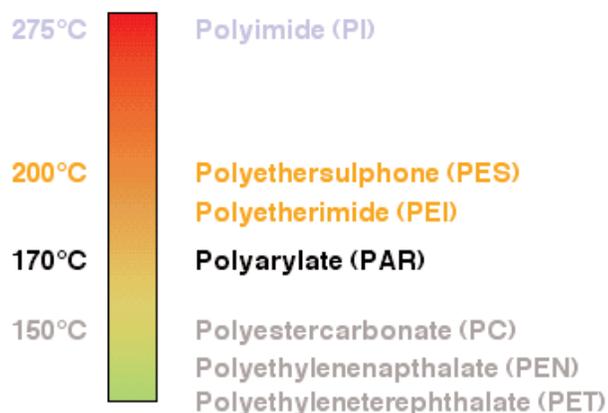


FIGURE 32
Potential candidates for OLED substrates.

For OLED display applications, substrate materials must meet stringent requirements: Optical transmittance of 90% from 400 nm to 700 nm and 85% with ITO coating. The substrate must be stable under heat. The instabilities under heat would preclude all operations requiring higher deposition, conditioning, or drying temperatures. Thermal expansion should be <5 x 10⁻⁵ / °C with 5% variation. Thermal shrinkage, 0.1% after 200°C for 1 hr, with 5% variation. The specifications for general lighting purposes are expected to be similar.

The one OLED-related issue here besides the transparent conductor material itself is the surface roughness requirements. A common specification is surface R< 20 nm. Applied Films has recently developed a “smooth” ITO for the OLED community with claims of R< 10 nm.

Also, the polymeric substrate must be essentially free of low molecular materials — ingredients that could leach out of the bulk and affect the performance of OLEDs.

There is a need for a new OLED substrate polymer with

- high thermal resistance to at least 200°C — shrinkage or expansion free
 - >90% transparency
 - minimum surface roughness
 - low oxygen permeability ($<10^{-5}$ cc.m² per day)
 - low water permeability (<1 mg/m² a day)
 - the virtual absence of defects (crystals, bubbles, filaments, etc.)
-

3.2.6 Summary: Technological Roadblocks

This chapter showed what the technological roadblocks and challenges are in this stage of OLED development. The tasks for dealing with the challenges are formidable. Some of the challenges are evolutionary in nature but others require breakthroughs and inventions: However, no fundamental or theoretical obstacles have been identified that would prevent OLEDs from achieving the goal of becoming the commercial source of light.

Even though fundamental roadblocks do not exist, many incremental advances 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 of OLEDs and particularly to the design and synthesis of novel high performance materials. The lack of high performance materials (charge transport small molecules and polymers, stable singlet and triplet emitters with the right emission spectrum, etc.) is the major obstacle in achieving the goal.

Summary: Challenges and roadblocks:

- The OLED power efficiency is low.
 - The operating life of OLEDs is too short.
 - Light extraction from OLED devices is poor.
 - The quality of white color is still not acceptable.
 - There are no known alternatives to ITO.
 - There are no obvious alternatives to the current cathode metals.
 - Effective barrier materials are needed.
 - Substrate polymers, tolerating high temperatures have not been identified.
 - The Impact of handling large currents and connections to OLEDs is not understood.
 - Manufacturing technology for large OLED devices has not been established.
-

3.3 Needed Research Activities

The review of short-term (2-5 y) and long term (5 - 10 y) technological challenges and roadblocks shows that major research activities are needed in the following areas:

- Mechanism of luminescence and phosphorescence, and design of new emitters.
- Mechanism of degradation of OLED components.
- Conversion efficiency, including light extraction from OLED devices.
- Color design.
- Methods of achieving stable white light.
- General area of materials design for improved performance.

3.3.1 Mechanism of Luminescence, Emitters

Objective: to achieve 100% luminescence efficiency, either by increasing the efficiency of photoluminescence above 25%, or by utilization of triplets, or both.

The basic mechanism of electroluminescence is quite well known by this time — both in small molecule films and in conjugated polymers. Unresolved areas include the importance of triplets. In *small molecule* systems, it is quite clear that triplets play an important role (the singlet-triplet splitting is sufficiently large that these are the proper quantum numbers). In this case, the maximum quantum efficiency of the photo-luminescence (PL) is believed to be 25%.

The recent development of high efficiency electro-phosphorescence using heavy metal complexes to efficiently harvest triplets (via triplet emission) is an important step. The situation in conjugated polymers is less clear. Demonstration by several groups of EL quantum efficiencies greater than 25% of the PL (19) suggests that triplet formation is less important in polymer LEDs. Nevertheless, the use of heavy metal complexes in polymer LEDs should be explored as dopants, side chain functionalities or even separate layers etc.

Alternative mechanisms should be also explored. The Light-emitting Electrochemical Cell (LEC) is an excellent example. If the basic electrochemistry problems can be solved, the LEC approach offers a number of advantages, including high brightness at low voltages and balanced injection (a requisite for high efficiency).

3.3.2 Elucidation of Mechanism of Degradation

Objective: To develop understanding of pathways leading to photochemical and electrochemical changes of active materials and to develop means of preventing these changes.

There have been relatively few detailed studies of degradation mechanisms in both polymers and small molecules, and at interfaces between layers. In the case of polymers, with a deeper understanding of the degradation mechanisms, one can “get smart” with the synthesis (e.g. to avoid specific defects, to avoid reactive sites, etc). Small molecules which have stable, unreactive cation-radical (the resident charge carrier - hole) have to be designed and synthesized. The chemical nature of interactions between interfaces (such as metal-to-polymer) has to be understood. Until we understand the principal degradation mechanisms, we will be working on a trial-and-error basis. Research in this area is badly needed and should be encouraged.

3.3.3 Device Conversion Efficiency, Light Extraction

Objective: Application of known engineering solutions for light extraction to OLED devices. Increased luminescence and phosphorescence efficiencies through materials design. Identification of novel efficient and stable triplet emitters.

The issues here relate back to the mechanism(s) of electroluminescence, and to the optical engineering issues involved in getting the emitted light out. Device architecture can have a strong effect. For example, the use of microcavities can be used to tune the wavelength and the bandwidth of the emission color from a broad band emitter. The microcavity also narrows the emitted beam into the forward direction. This forward-directed emission simplifies the light extraction problem as well. Thus, the incorporation of microcavities in the device architecture may offer specific advantages. A disadvantage is that the apparent color (in a monochrome device) becomes dependent on the viewing angle. This has not yet been explored in the context of white lighting; simulation studies would provide guidance. The methods of texturing the interfaces, the utilization of index-matching fluids, modification by arrays of lenses etc. have to be explored and assessed with respect to the feasibility of manufacturing.

Organic phosphors are nearing 100% internal quantum efficiency at low drive voltage. Triplet-triplet annihilation decreases the efficiency at higher drive. Methods ought to be found to reduce the effect of triplet-triplet annihilation, perhaps by designing shorter lifetime phosphors. It appears that the singlet-triplet ratio in fluorescent OLEDs can be pushed further to the triplet side. Some fluorescent polymers already claim > 25% internal efficiency in the device, suggesting other than a 3:1 triplet : singlet ratio. This phenomenon is not understood and requires a major research effort.

The index of refraction (n) of organic luminescent semiconductors is much less than that in inorganic semiconductors (an important advantage of the OLED technology). Nevertheless, the external efficiency is significantly reduced with respect to the internal quantum efficiency in OLEDs. For organic semiconductors, $n^2 \approx 3$. For isotropic dipole emitters (appropriate to amorphous films of small molecules), the external-to-internal efficiency reduction factor is $1/(2n^2) \approx 6$. For dipoles in the plane of the film (appropriate for conjugated polymer films), the reduction factor is $1/(n^2) \approx 3$. Thus, there is a straightforward path toward improvement of the light output by a signifi-

cant factor through optical engineering of the front surface. This is an area where much is known from previous engineering research. Innovative optical engineering approaches must be designed and implemented. Three approaches have been recommended: Either

- a) build a microcavity to force light out (directional) or
- b) use engineered substrate geometry, (12) or
- c) use optical roughening layer, (13).

Solving the light extraction problem is one of the major challenges facing the OLED community but the payoff would be high. A 100 % extraction efficiency would mean an improvement by a factor of 6 in the external efficiency of OLEDs.

3.3.4 White Light

Objectives: Obtain the understanding of what kind of “white” output is needed for general lighting applications. Develop stable emitters, or different color emitters.

An equivalent to T=6300K) with CIE coordinates 0.32, 0.32 is within the reach of both polymeric and small-molecular OLEDs. The desired 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* high color rendition index is important. Also, **differences still exist in the rate of aging of devices of different colors.** For the white light applications it means that as the light source ages, the color will change. For luminances that are needed for general lighting (of the order of 850 cd/m² and higher), perceptible changes in the quality of white would now occur within weeks or even days of operation. This is a major roadblock and a major research effort should be directed towards designing *stable* emitters, both polymeric and small molecule, singlet and triplet.

3.3.5 Color Design

Objective: To develop a sufficient inventory of stable emitters to tune color to any desired position on the chromaticity diagram and the color rendition index.

This OLED technology is definitely materials limited. The lack of adequate materials is holding back the progress of OLEDs. At this time, stable, **high efficiency materials with sufficient lifetime to provide the red, green and blue needed for stable white light are simply not available.** Basic research on new materials is needed. Complex multi-step syntheses will be a barrier to the low cost needed for lighting applications. Although there is an opportunity here for important contributions by university groups, it is critically important that industrial laboratories be involved. The need for ultra-high purity and the need for commercial scale production must be recognized from the beginning. Thus, “clean room” synthesis will be needed, analogous to that employed in the photoresist industry.

3.3.6. Materials Design for Performance and Stability

Objective: To address peripheral issues of incompatibilities between different layer materials such as adhesion, intermixing, chemical reactions, differences in thermal expansion coefficients, etc. These issues can be resolved by an across-the-board increase in inventories of active OLED materials

The lack of high-performance materials in all parts of the OLED device architecture is the major factor that holds back the progress in the OLED field. There exists a severe lack of choices among materials. The major deficiencies of existing material components on OLEDs are summarized in Table IX.

Adjacent layers in the OLED devices face other kinds of incompatibilities which could be also eliminated by changing the materials: adhesion problems; differential thermal expansion, deposition techniques, undesirable intermixing. Increased materials research and expansion of choices would significantly accelerate the development of OLEDs.

3.3.7 Lasers

Although lasers may not be directly relevant to lighting applications, the understanding of principles of lasing in organics and device architecture issues may help in designing OLEDs with high light extraction efficiencies.

Organic lasers could be used in a variety of applications and are an area of active research. The first organic injection laser was recently demonstrated (Science, Aug 7, 2000). Handling the heat generated in organic lasers will be intrinsically difficult, since these materials have low thermal conductivities compared to single crystal inorganic semiconductors. Micro-lasers with colors that span the visible spectrum will generate a variety of applications. The development of organic injection lasers is an area of major opportunity, but somewhat orthogonal to the lighting application technology roadmap.

Table XI. Limitations of Existing OLED Materials Requiring Major Research Activities

Existing Material Components	Major Deficiencies
Substrate	Surface defects; Low T _m ; shrinkage / expansion at elevated temperatures; adhesion
Anode	Low conductivity; brittleness; pinholes; light absorption; difficult deposition; injection barriers
Cathode	Extreme reactivity towards moisture and oxygen; reactivity with adjacent layers; injection barriers; lack of transparency; difficult deposition
Hole Transport SM	Low carrier mobility; low T _g ; degradation of charge transport; deposition only by sublimation;
Electron transport SM / Emitters	Limited colors to achieve "good" white; limited carrier range; deposition only by sublimation;
Charge Transport Polymers / Emitters	Structural defects, stability; photochemical degradation; limited color of emission
Singlet Emitters	Photoluminescence efficiency at high V; differential aging of different colors, choice of emission spectrum; limited colors to achieve "good" white
Triplet Emitters	Limited choice of color; low efficiency; chemical reactivity in excited state; uncontrolled singlet - triplet ratio; limited colors to achieve white
Barriers, Encapsulators	Permeation to oxygen and water

4 Performance and Cost Goals

4.1 Performance Goals

OLED Efficiency vs. Wavelength

For white light in display applications the industry would like to see the CIE coordinates 0.32, 0.32. White color (an equivalent to $T=6300\text{K}$) with these coordinates is within the reach of both polymeric and small-molecular OLEDs (see, for example Figs. 11 and 12). For certain limited applications the existing numbers are already adequate. The existing devices, however, are far from meeting the life and efficacy requirements.

However, getting the CIE coordinates, which are specified for display applications may not necessarily be acceptable for general lighting applications. The current devices do not have the desired high color rendition index. The definition of “good” white for general lighting has to be developed on the basis of customer preference. Broad spectra of organic emitters give OLEDs an advantage in fine tuning the shades of white. White light is produced by incandescent lamps where the filaments is heated to 2800 - 6000K. In OLEDs, the white light emission is achieved by appropriate mixing of colors, narrow or broadband, using selected emitters or dopants.

A fundamental trade-off exists between CCT / CRI and luminous efficacy (lumens per watt (lm/W)). Optimal existing devices with acceptable white light have luminous efficacy ranging from 300 - 400 lm/W. Therefore, an OLED SSL source with 100% electrical to conversion efficiency would have an efficacy of about 350 lm/W. In order to compete with the fluorescent lighting market, the efficacy of OLED sources should be 120 lm/W, which is 20-40% better than the best achieved current value. To achieve the needed 120 lm/W, the OLED source must have an electrical to optical power conversion efficiency of 34%. To effectively penetrate into the fluorescent lighting market and begin displacing it, the efficacy of 200 lm/W is desirable. This would mean an external device conversion efficiency of 57%.

It is essential that the CRI (color rendition index) exceeds 70. The current OLED technology already offers the CRI in the range of 50 - 85. To get the lumen output equivalent to a typical four lamp fluorescent fixture (32 W with 70% fixture efficiency), the brightness of 2,000 Cd/m² is needed, assuming that the light source area is the same, approx. 1.2 m². The need for brightness diminishes as the area of the source increases, which mitigates the brightness requirements for OLEDs. To eliminate the glare problem, the large area lighting fixtures should not be brighter than 850 cd/m².

Operating Life

To achieve parity with the current fluorescent lighting technology, the lifetime greater than 10,000 hrs is required. Lifetime is now defined as an average number of hours of operation in which the initial light intensity drops to 80%. However, for applications where a new light source will be used in the proximity of the aged light source,

the life requirements will have to be much more stringent. For example, the display industry experience suggests that only a 5% drop in output (to 95% of the original brightness) would be acceptable to the customer. This is all assuming that all colors, which form the white will age in with the same rate. A slight change in color due to differential aging of the emitters will be also highly objectionable. The customer acceptance of the change in the CIE coordinates of the white light output has not yet been quantified.

4.2 Cost Goals

Recent studies show that for effective market penetration, <\$6.20 per klm (kilolumen) for 120 lm/W SSL (57% power efficiency) is required. The cost of fabrication, assuming \$6.20 / klm and 2,000 Cd/m² brightness of the light panels should be less than \$39/m².

Table XII. Cost of Light Comparison: SSL vs. Fluorescent Sources (5)
Cost of 1000 Lumens of Light for 20,000 hrs

Source Type	Unit Source Cost	White Light Efficacy	Electricity Usage	Total Cost of Light
Fluorescent	\$2.25	100 lm /W	286 kWh	\$23.96
SSL (34% efficient)	\$6.21	120 lm /W	57 kWh	\$18.88
SSL (100% efficient)	\$9.86	350 lm /W	25 kWh	\$14.20

Assumptions:

Electricity cost \$0.076 /kWh

Fluorescent unit cost includes ballast cost per kilolumen per 20,000 hrs

Fluorescent fixture efficiency assumed to be 70%

Luminous efficiency, turn-on voltage and lifetime are the main factors affecting the success of OLEDs as light sources. The advent of electrophosphorescent devices has greatly improved the outlook for OLED efficiency by raising the limit on internal quantum efficiency from 25% to 100%. Efforts in OLED research have not concentrated on improving photon extraction, so that the external quantum efficiencies of OLEDs are still limited. However, in view of the momentous increases in the efficiencies of inorganic LEDs due to improvements in photon extraction, it is not unreasonable to expect that similar advancements in the extraction efficiencies of OLEDs will be achieved in the near future. Although high OLED efficiencies can be obtained at turn on voltages below 10 V, the maximum brightness is usually achieved between 10 - 20 V. Compared to conventional inorganic LEDs, OLEDs can offer comparable efficiencies for area sources while possessing greater ease of fabrication (i.e. much lower manufacturing cost), greater color tuning ability and flexible light sources.

5 References

1. J. R. Brodrick, OLED Workshop Nov. 30, 2000.
2. C. W. Tang, S. A. Van Slyke, C. H. Chen, Appl. Phys. Lett. 65, 3610 (1989).
3. J. H. Burroughes et al., Nature 347, 539 (1990).
4. H. Antoniadis, OLED Workshop Nov. 30, 2000. Adapted from a graph by J. Sheats, Hewlett Packard.
5. A. Duggal, OLED Workshop Nov. 30, 2000.
6. S.A. Van Slyke, (Eastman Kodak), OLED Workshop Nov. 30, 2000.
7. R. H. Friend, Nature, 397, 121 (1999)
8. Covion, Advanced Materials 12, 42 (2000).
9. M. Thompson et al., OLED Workshop Nov. 30, 2000.
10. H. Becker, et al., Phys. Rev. B 56, 1893 (1997)
11. I. Schnitzer and E. Yablonovich, Appl. Phys. Lett., 63, 2174 (1993).
12. G. Gu et al., Opt. Lett. 22, 396 (1997).
13. C. Madigan et al., Appl. Phys. Lett. 76, 1650 (2000).
14. T. Yamasaki et al., Appl Phys. Lett. 76, 1243 (2000).
15. Latest results published on the web site:
<http://www.cdtltd.co.uk/newresultsBanner.htm>
(Cambridge Display Technology / Aventis / Dow Chemical)
16. Y. Ohno, NIST, OLED Workshop Nov. 30, 2000.
17. H. Becker, (Covion), presentation at the FPD Manufacturing Technology Conference, Feb. 2-3, 2000, San Jose, CA.
18. C. W. Tang, S. V. Slyke, Eastman Kodak Co.
19. H. Antoniadis, OLED Workshop Nov. 30, 2000.
20. T. Tsutsui, et al., Appl. Phys. Lett. 76, 1243 (2000))

6 Glossary of terms

CCT Correlated color temperature	POLED Light emitting polymer
cd Candela	R_e Extraction coefficient
cd/m² Candelas per square meter	SM Small molecule
CDT Cambridge Display Technology	SST Solid state lighting
CRI Color Rendition Index	T_g Glass transition temperature
eV Electron volt	T_m Melting temperature
HID High intensity discharge	UDC Universal Display Corporation
ITO Indium - tin oxide	USC University of Southern California
klm Kilolumen	V Voltage (Volts)
L Luminance	W Watt
LEC Light-emitting electrochemical cell	η_{ext} External efficiency
LED Light emitting diode	η_{int} Internal efficiency
LEP Light emitting polymer	Φ_f Quantum efficiency of fluorescence
lm Lumen	
n Refractive index	
OLED Organic light emitting diode	
PE Polyester	

7 Acknowledgement

I would like to express my gratitude to Arpad Bergh for his guidance and invaluable comments in drafting this report. I would also like to thank Alan Heeger, Homer Antoniadis, Ed Petrow, Chips Chipalkatti, Julie Brown, Anil Dugal, Steve Johnson, Steve Van Slyke, John Ryan, and Paul Burrows, — all participants of the Nov. 30 - Dec.1, 2000 Workshop on OLEDs for helping me to put this status report together and for sending me all the data, comments, suggestions and advice, and for answering all the questions I had in the process. Also, I would like to thank Arpad Bergh for the suggestion to include in this draft a copy of the chapter on Color Issues of White-Light from the draft “Solid State Light Emitting Diodes for General Illumination” written by Dr. Yoshi Ohno from the Optical Technology Division, National Institute of Standards & Technology (NIST). Special thanks are directed to Diane Burnes for reminding me to stay on schedule.

Milan Stolka

PART 2

Conclusions and Recommendations

of the Nov. 30 - Dec. 1, 2000
Workshop on OLEDs for General Lighting

1 Introduction

The workshop on OLED-based SSL for general illumination was attended by approximately 35 representatives from universities, industry, government laboratories, the Department of Energy. The main objective of the workshop was to identify and qualify roadblocks in the way of making OLEDs a technology aimed at replacing the fluorescent lighting, and to develop consensus on the course of action to achieve this ambitious goal.

A general agreement was reached that there are no *fundamental* — theoretical obstacles for OLEDs to become a technology of choice for general lighting. However, there still exists a number of “*incremental*” roadblocks that have to be overcome, many of which require inventions or major breakthroughs.

It was also agreed that most of these roadblocks are materials related. The rate of progress will depend on the success in designing and synthesis of novel high performance, stable materials components of OLED devices to replace those that are still deficient.

- Part one of the conclusions deals with the requirements for achieving stable energy-efficient OLED devices capable of competing with and eventually replacing fluorescent lights.
- Part two summarizes the long term research, development and manufacturing issues.
- Part three presents a summary of the current status of OLED research and development.
- Part four describes the status and projections based on the current knowledge of issues and the pace of progress that OLEDs have experienced.

2 Requirements for making OLEDs the Technology of Choice for General Lighting

Achieving white light with the desired position on the CIE chromaticity diagram and with high color rendition index is within the reach of both polymeric and SM OLEDs. There already exists a large variety of emitters and many more will be designed which will provide the desirable emission spectra. The power efficiency requirement of at least 120 lm/W is also viewed as achievable, provided that a significant research and development program to design new stable materials is undertaken.

OLEDs will be useable for general lighting after the following improvements and changes are made:

- Higher white light device efficiency is achieved, by a factor of 10 or so.
- The operational lifetime is increased by approximately 10 - 15 times.
- Novel flexible plastic substrates, which will allow high temperature deposition of the device components, are identified.
- Manufacturability of large area (distributed) light sources is established.
- The issues of packaging are resolved
- The infrastructure for handling large electric currents (at low voltages) to drive OLEDs is in place.

It is agreed that these are the main areas of future development activities and each will require substantial investments in time, manpower and money.



There are two main groups of OLED devices, both operating on the same principle but using two different groups of materials: “Small molecule” (SM) OLEDs, and polymeric OLEDs (POLEDs). Both materials systems have achieved about the same level of stability, device efficiency, color design etc., and therefore, it is not advisable to prefer one of these two sets of materials to the other at this time.

SM OLEDs: This group appears to have achieved more attention because the synthesis and mainly purification of organic small molecules is easier and straightforward. However, the devices based on SMs are more complex than polymeric devices. They have up to 9 layers which poses a significant manufacturing (and cost) challenge. In addition, some of the layers are deposited by sublimation of the small molecules, which again is not easily scaleable. The discovery that triplet states can be harvested in SM devices to produce photons gave this group a significant momentum.

POLEDs: The light emitting devices based on polymeric materials are simpler, with fewer layers. The polymers are deposited by solution coatings, which is much easier to scale up and less expensive. In addition, the yield of singlet states was found to exceed 25%, which increased the chance of success of POLEDs. However, the synthesis and purification of the type of polymers used in light emitting devices is difficult. Unfortunately, there appears to be only a minimum synthetic effort in place in the US, which slows down the progress. In spite of the lack of polymer synthetic activities in the USA it is reasonable to expect that POLEDs will continue to play an important role in the family of organic LEDs. European laboratories such as Cambridge Display Technology have achieved a significant progress in the development of POLEDs and are effectively competing with the SM devices in the US and Japan.

Conceivably, both materials groups can be combined in one type of devices. The main reason why the combination has not been contemplated is the chemistry skill background of the researchers working on OLEDs. The organic chemistry and synthetic polymer chemistry skills are usually not available in one organization.

White color is achieved in both types of devices by mixing or stacking layers of the light emitting materials. White light of the desired T~6000K was generated in both groups of devices but further refinement is needed to get high CRI. New emitters have to be designed, synthesized and explored to achieve the desired operational life in both groups of devices.

3 Long-Term Research and Development Issues

A consensus has been reached that most of the future research and development effort should be materials related.

- Understanding has to be developed of the **degradation processes and mechanisms**. OLED devices can be bright at the onset of operation but the luminance decreases with time. The decay is faster at high luminances. The detailed mechanisms are not known. Several materials components can decay or react at the same time with passage of an electric current. Major systematic studies of aging of all material components (substrates, electrodes, injection-modifying layers, charge transport molecules, emitters, dopants, exciton blockers etc.) are needed. This type of research would be best carried out in *universities or national laboratories with an established expertise in electrochemistry*.
- Long term research should be carried out on the **singlet and triplet emitters** to improve the understanding of the excitons and to increase the efficiency of luminescence and phosphorescence. These studies and the synthesis of new emitters should be carried out with the main emphasis on increasing the operational life of these compounds. The research of emitters should be carried out in *universities with an established expertise in photochemistry and photophysics*.
- **Light extraction and device architecture**. Industrial labs should assume the leading role of this research area, mainly because the area is closely related to manufacturing issues. Several techniques are being explored, each presenting a manufacturing challenge (application of index matching fluids, corrugated surfaces and interfaces, microcavities, microlenses, etc.). The current flat devices allow less than 20% of the generated light to escape. The rest is lost by internal absorption, waveguiding, etc.
- Development of novel **conductive materials** with high optical transmissivity, the desired work functions and easy to deposit in uniform layers. The currently used anode, ITO, is expensive, brittle, and too resistive to deliver current to large areas, difficult to deposit. Similarly, the cathode metals (alloys of Ag with Li, Mg etc.) are too reactive, not only with the ambients but also with the adjacent device components, and have to be replaced, if at all possible. “Synthetic metals” (conductive polymers) would be the best solution but the existing conductive polymers do not possess the desired conductivity, stability and transparency. Solving this problem will be a result of the collaborative effort of *universities and the industry*, driven by the latter.
- **Generation of white light** with the right position on the CIE coordinates and high CRI. Even though OLEDs will deliver anything that the customer may require by the design of emitters, it is still not clear how the combine spectrum of the emitters should look like and how many emitters will be needed. The main issues are the stability of all emitters, and in the case of triplet emitters, the avail-

ability of blue. The issue of white light quality will be best tackled by the collaborative effort of *national laboratories (such as Lawrence Berkeley), academia and industry.*

- **Infrastructure and powering of OLED devices.** Even though this is not a purely scientific topic, forward thinking has to be initiated as soon as possible. The delivery of large currents will necessitate major changes in the ways power is handled and distributed in buildings and also how the OLED devices are connected to the power source. There is no expertise available in the OLED community and, therefore, the workshop participants did not discuss the subject. It is believed that the leading role belongs to the *industries* which plan to manufacture the OLED lighting devices and should be handled in collaboration with the *government labs such as LB Lighting Research Lab and institutions such as RPI Lighting Institute.*
- **Packaging.** In the context of OLEDs, packaging means two things: First, the protection of OLED devices from the access of moisture and oxygen (encapsulation). Second, it is the actual shape, configuration and powering of the lighting fixtures, including presenting it to the customer. The protection against the ambients is a part of ongoing studies aimed at increasing the operational life of OLEDs. The development of the latter should begin with a dialog between the device makers and fixture designers, engineers and architects. The leading role belongs to the *national labs and industries.*
- **Manufacturing research** has already begun by devising coating fixtures, evaporators, coaters, etc. Roll-to-roll coating is viewed as the only cost effective method of making large area OLED devices. Methods of incorporating evaporation / sublimation techniques are being pursued. The experience and expertise acquired in the development and manufacturing of organic photoreceptors for electrostatic printers by roll-to-roll precision coatings could be applied in designing the manufacturing facilities for OLEDs. The leading role belongs to the *industry.*

4 Current Status of OLEDs

a. Power Efficiency of OLEDs

No fundamental insurmountable roadblocks in increasing the device efficiency have been identified. In fact, given recent improvements, it is recommended that the application for general lighting be pursued aggressively as soon as possible. The OLED internal efficiency η_{int} is the number of generated photons per number of injected charge pairs. Ideally, all injected charge pairs should 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 hole injection is balanced with electron injection. Unequal injection rates result in a free passage of one sign carrier and thus to wasteful passage of current. 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.*

Based on a spin statistics, the singlet excitation efficiency η_s was believed to have a maximum value of 25%. 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 electroluminescence. 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 well 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 now only in dilute solutions. General problem is to maintain high Φ_f in solid state. Few materials now have Φ_f greater than 50% in OLEDs. However, progress has been made in this area as well.

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 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 than the optimum. 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:

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

In view of the recent development it is possible that the internal device efficiency can be eventually raised to values that are close to the fundamental limit of unity (100%).

In addition to the internal inefficiencies, there exists a problem with the “extraction” of photons from the device. Over 80% of the light have been 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.

The external efficiency η_{ext} is related to the internal efficiency by a formula

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

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.

It is believed that the extraction efficiency can be increased above 80% with appropriate patterning of the reflective substrate.

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.

There was much discussion regarding the luminance level required. If the entire ceiling is emitting, a luminance level of 100 cd/m² is necessary (this will give 100 cd/m² 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/m². The lighting industry will not accept greater than about 850 cd/m² for glare reasons and, for 850 cd/m², approxi-

mately 12% of the ceiling area would be required for lighting. *A luminance level of 850 cd/m² 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.

b. Life

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.

Short device life is a major obstacle to commercialization of OLEDs for general lighting. 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 life as a main 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 government / industry / 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, CO₂ 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 still age with different rates.

c. Color

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. 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.

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

The polymeric systems, which are attractive from the device simplicity point of view, are hampered by the lack of polymer design activity. Color is controlled by the structure of the polymers. 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.

d. 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.

- Develop OLED technology that meets the performance specification at acceptable cost. The cost target for near term goals is \$20/m². It is estimated that the present cost for OLED technology is \$400/m².
- Perform basic materials development work to simplify and reduce the manufacturing costs.

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. It is believed that the manufacturing cost could be \$50/m² in 2003 and \$20/m² 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

5 Goals and Milestones

The following projections are based on the existing rate of progress in achieving the main performance goals. No differentiation has been made between SM OLEDs and POLEDs because both groups of materials are viewed as having the same chance of success. Also, an assumption has been made that an effective framework for the government / industry / academia collaboration will be established and additional resources will be available.

Goals and Milestones for the development of OLEDs

Subject		Impact/ Focus	Goals / milestones		
			1y	3 y	6 y
Operational lifetime at 1000 cd/m ² , (hrs)		Degradation processes understood / controlled	1,000	5,000	20,000
Singlets - internal efficiency, (%)		POLEDs improved	15	20	40
Triplets - internal efficiency, (%)		SM OLEDs improved	62	75	80
Light extraction efficiency, (%)		Manufacturing challenges solved	40	60	80
White color (6000K)		Tunable color also enabled. Color of choice.		Achieved	Achieved
CRI		Quality of light approaching/ exceeding lightbulbs	75	85	100
Current density for white at 850 cd/m ² , (mA/cm ²)		Large area illumination (panels, ceilings) enabled	20	6	2
Operational voltage for white, (V)		Large area illumination (panels, ceilings) enabled	7	4	3.5
2 x 4 fixture	Luminous output (1000 cd/m ²)	Replacement of 2335 fluorescent lamps		2335	
	Total current, (A)	Replacement of fluorescent lamps	149	80	15
	Input power, (W)	Replacement of fluorescent lamps	1041	250	52

At this stage of OLED development there is no large scale manufacturing facility available. It is also not clear at this time if roll-to-roll coating could be fully applicable for manufacturing of OLEDs or some form of large-scale vacuum deposition methods would have to be developed.

Issue	Impact, Focus	Goals / milestones		
		1y	3 y	6 y
Plastic substrate: replacement of polyester	Better, defect-free, high temperature plastic substrates	No replacement available	Polysulfones (?)	Polyamides, polyimides, etc.
Large area coating of OLED panels	Cost competitive large scale manufacturing	Single layer, roll-to-roll coating	Multiple layers, different solvents, drying conditions determined	Roll-to-roll coating combined with vacuum deposition
Packaging / encapsulation	Protection of OLEDs against ambients	Methods proposed and evaluated	Manufacturability assessed	Optimum techniques identified and tested
Infrastructure / device powering	New paradigm in powering light fixtures	Dialog with architects, utilities, etc. initiated	Feedback provided to OLED manufacturers	Standards set, manufacturing ready

The time-scale of the manufacturing issues will strongly depend on the timing and the level of support that the OLED technology may receive.

Appendix I: OLED Solid State Lighting Workshop Agenda

Thursday, November 30, 2000

- 8:00 Continental Breakfast
- 8:30 Welcome – Arpad Bergh, *OIDA*
- 8:45 DOE Perspective/Energy Saving Potential – Ed Petrow, *U.S. Dept. of Energy*
- 9:00 Background and Logistics of Workshop – Milan Stolka, *Imaging Systems Solutions*

Applications and Markets

- 9:30 Lighting Industry Perspective – Steve Johnson, *Lawrence Berkeley National Labs*
- 9:50 Solid State White Light Architectures – Yoshi Ohno, *NIST*
- 10:10 New Market Potential and New Uses for OLEDs – Karl Drexler, *Infineon*
- 10:30 Break

Technology Issues

- 10:50 Materials, Design, Synthesis, Purification – Mark Thompson, *Dept. of Chemistry, USC*
- 11:10 “Small-Molecular” Devices: Technological Roadblocks, Breakthroughs Needed – Steve Van Slyke, *Eastman Kodak*
- 11:30 Polymeric OLEDs: Technological Roadblocks, Breakthroughs Needed – Nick Colaneri, *Uniax*
- 12:00 Lunch
- 1:30 Light Extraction from OLED Devices – Homer Antoniadis, *Infineon*
- 2:00 Performance Requirements & Cost Goals of OLEDs – Anil Duggal, *GE*
- 2:30 Encapsulation and Packaging – Paul Burrows, *Pacific North West National Lab*
- 3:00 Breakout Session
 - Group I – “Small Molecular” Devices – Steve Van Slyke
 - Group II – Polymeric OLEDs – Paul Burrows
- 4:30 Breakout Group Reports
- 5:00 Discussion
- 5:30 Adjourn
- 6:30 Reception

Friday, December 1, 2000

8:00 Continental Breakfast

Manufacturing Challenges and Recommendations

8:30 Tuning Color and Achieving White Light from OLEDs –
Steve Forrest, *Princeton University*

9:00 Manufacturing Challenges – Julie Brown, *Universal Display Corporation*

9:20 Roll-to-Roll Coating – James Sheats, *Rolltronics*

9:40 SSL Industry & OLED Initiatives Outside the US –
Steve Forrest, *Princeton University*

10:00 Framework for National Industry & Government Initiatives – Ed Petrow, *DOE*

IP Issues – Joseph Paladino, *DOE*

Planning Process – Doug Brookman, *Public Solutions Inc.*

10:20 Breakout Session

Group I – OLED Breakthrough Technologies and Roadblocks – Homer Antoniadis

Group II – Manufacturing Technology Challenges and Cost Reduction – Julie Brown

12:00 Lunch

1:00 Breakout Group Reports

1:30 General Discussion

2:00 Conclusions – Arpad Bergh, *OIDA*

2:15 Tour of Berkeley

Appendix II: Workshop Attendees

Kimberly Allen

Stanford Resources
20 Great Oaks Blvd., Suite 200
San Jose, CA 95119
Ph: 408-360-8400
Fax: 408-360-8410
E-mail: k.allen@stanfordresources.com

Homer Antoniadis

OSRAM Semiconductors
3870 North First Street
San Jose, CA 95134
Ph: 408-456-4004
Fax: 408-456-4305
E-mail: homer.antoniadis@infineon.com

Norman Bardsley

LLNL
L-395, 7000 East Avenue
Livermore, CA 94551
Ph: 925-422-6008
Fax: 925-422-8761
E-mail: bardsley1@llnl.gov

Arpad Bergh

OIDA
2010 Massachusetts Avenue, NW
Suite 200
Washington, DC 20036-1023
Ph: 202-785-4426
Fax: 202-785-4428
E-mail: aboida@osa.org

Jan Bernkopf

Alien Technologies
900 E. Hamilton Ave, Suite 100
Campbell, CA 95008
Ph: 408 879 7326
Fax: 408 879 7335
E-mail: jbernkopf@alientechnology.com

James Brodrick

DOE
1000 Independence Avenue, SW
Washington, DC 20585-0121
Ph: 202-586-1856
Fax: 202-586-4617
E-mail: james.brodrick@hq.doe.gov

Doug Brookman

Public Solutions
5 Ingleside Avenue
Baltimore, MD 21228
Ph: 410-719-0580
Fax: 410-719-0581
E-mail: pubsolns@clark.net

Julie Brown

Universal Display
375 Phillips Blvd
Ewing, NJ 08618
Ph: 609-671-0980
Fax: 609 671 0995
E-mail: jjbrown@universaldisplay.com

Paul Burrows

Pacific Northwest National Lab
902 Batelle Blvd.
PO Box 999
Richland, WA 99352
Ph: 509-375-5990
Fax: 509-375-3864
E-mail: burrows@pnl.gov

Nicholas Colaneri

UNIAX
6780 Cortona Drive
Santa Barbara, CA 93117-3022
Ph: 805-562-9293 x110
Fax: 805-562-9144
E-mail: nick@uniaux.com

Karl Drexler

Infineon
3870 North First Street
San Jose, CA 95134
Ph: 408-456-4029
Fax: 408-456-4305
E-mail: karl.drexler@infineon.com

Anil Duggal

General Electric
1 Research Circle, Room K1-4C25
Niskayuna, NY 12309
Ph: 518-387-7424
Fax: 518-387-5714
E-mail: duggal@crd.ge.com

Stephen Forrest
Princeton University
B 210, Dept. of EE
Olden Street
Princeton, NJ 08544-5263
Ph: 609-258-4532
Fax: 609-258-0119
E-mail: forrest@ee.princeton.edu

David Iams
OIDA
2010 Massachusetts Avenue, NW
Suite 200
Washington, DC 20036
Ph: 202-785-4426
Fax: 202-785-4428
E-mail: dioida@osa.org

Steve Johnson
Lawrence Berkeley Natl Lab
1 Cyclotron Road, MS 90-3111
Berkeley, CA 94720
Ph: 510-486-4274
Fax: 510-486-4089
E-mail: sgjohnson@lbl.gov

John Kerr
Lawrence Berkeley National Lab
1 Cyclotron Road, MS 62-203
Berkeley, CA 94720
Ph: 510-486-6279
Fax: 510-486-4995
E-mail: jbkerr@lbl.gov

Qonnie Laughlin
DOE
FORS Bldg - Room 1J-018, MS 6A-116
Washington, DC 20585
Ph: 202-586-9632
Fax: 202-586-4617
E-mail: qonnie.laughlin@hq.doe.gov

Ron Lewis
DOE
1000 Independence Avenue, SW
Rm. 1J018
Washington, DC 20585
Ph: 202-586-8423
Fax: 202-586-4617
E-mail: ronald.lewis@ee.doe.gov

Heng Liu
AXTI
2019 Saturn Street
Monterey Park, CA 91754
Ph: 323-278-0820
Fax: 323-278-0096
E-mail: hengl@axt.com

John McMahon
Vitex Systems
1225 Tiros Way
Sunnyvale, CA 94085
Ph: 510-848-8480
Fax: 253-423-9159

David Mentley
Stanford Resources
20 Great Oaks Blvd., Suite 200
San Jose, CA 95119
Ph: 510-669-0521
Fax: 408-360-8410
E-mail: d.mentley@stanfordresources.com

Yoshi Ohno
NIST
100 Bureau Drive MS 8442
Gaithersburg, MD 20999-8442
Ph: 301-975-2321
Fax: 301-840-8551
E-mail: ohno@nist.gov

Joe Paladino
DOE - NETL
3610 Collins Ferry Road
Morgantown, WV 26507-0880
Ph: 304-285-4526
Fax: 304-285-4100
E-mail: joseph.paladino@netl.doe.gov

Mookkan Periyasamy
DuPont Technologies
Experimental Station, Bldg 334/124
Wilmington, DE 19880
Ph: 302-695-3433
Fax: 302-695-2341
E-mail: mookkan.periyasamy@usa.dupont.com

Edward Petrow
DOE
341 Lincoln Road
Sudbury, MA 01776
Ph: 978-443-5659
Fax: 978-443-1336
E-mail: edward.petrow@ee.doe.gov

Edward Pollock, Jr.
DOE
FORS Bldg - Room 1J-018, MS 6A-116
Washington, DC 20585
Ph: 202-586-9127
Fax: 202-586-4617
E-mail: edward.pollock@hq.doe.gov

James Pugh
LBNL
1 Cyclotron Road
Berkeley, CA 94720
Ph: 510-486-7397
Fax: 510-486-4995
E-mail: jkpugh@lbl.gov

Victor Roberts
Rensselaer - Lighting Research Center
21 Union Street
Troy, NY 12180-3352
Ph: 518-687-7188
Fax: 518-687-7120
E-mail: roberv@rpi.edu

Stephen Selkowitz
LBNL
One Cyclotron Road, MS 90-3111
Berkeley, CA 94720
Ph: 510-486-5064
Fax: 510-486-4089
E-mail: SESelkowitz@lbl.gov

Charles Shank
Lawrence Berkeley Natl Lab
1 Cyclotron Road, Mailstop 50A-4119
Berkeley, CA 94720
Ph: 510-486-5111
Fax: 510-486-6720
E-mail: cvshank@lbl.gov

James Sheats
Agilent Technologies
1501 Page Mill Road
Palo Alto, CA 94304
Ph: 650-857-5987
Fax: 650-813-3152
E-mail: sheats@hpl.hp.com

Derrick Steinle
Boeing
Kennedy Space Center
PO Box 21233
Cape Canaveral, FL 32815
Ph: 321-799-7237
Fax: 321-799-6834
E-mail: derrick.r.steinle@boeing.com

Frank Steranka
LumiLeds Lighting
370 W. Trimble Road, MS 91ML
San Jose, CA 95131
Ph: 408-435-6636
Fax: 408-435-6039
E-mail: frank.steranka@lumileds.com

Milan Stolka
14 Park Circle
Fairport, NY 14450
Ph: 716-223-5309
Fax: 413-826-0259
E-mail: mstolka@rochester.rr.com

John Talbott
DOE
FORS Bldg - Room 1M-048, MS 6A-116
Washington, DC 20585
Ph: 202-586-9455
E-mail: john.talbott@hq.doe.gov

Ye Tao
National Research Council - Canada
M-50 Montreal Road
Ottawa, Ontario K1A 0R6 CANADA
Ph: 613-998-2485
Fax: 613-990-0202
E-mail: ye.tao@nrc.ca

Mark Thompson
USC – L.J. Stabler Laboratory
Los Angeles, CA 09989-0744
Ph: 213-740-6402
Fax: 213-740-8594
E-mail: met@usc.edu

Steve Van Slyke
Eastman Kodak
1999 Lake Avenue
Rochester, NY 14650-2110
Ph: 716-722-1222
Fax: 716-477-6498
E-mail: steven.vanslyke@kodak.com

Fred Welsh

OIDA
2010 Massachusetts Avenue, NW
Suite 200
Washington, DC 20036-1023
Ph: 202-785-4426
Fax: 202-785-4428
E-mail: fwoida@osa.org

Andrew Yang

OIDA
3041 N. Pollard St.
Arlington, VA 22207
Ph: 703-243-2231
Fax: 703-243-2124

