OLEDs: An Introduction To The Other Solid-State Lighting Technology

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Course Description

Up to now, LEDs have received all the press when it comes to lighting discussions. However, there is second member of the solid-state lighting family that is starting to attract attention. Organic Light Emitting Diodes, or OLEDs, are beginning to move from high priced novelty products to more mainstream illumination solutions. They are now even available in some big box stores. OLEDs offer new and exciting capabilities where the light becomes the luminaire. In this presentation, Dr. Curran will provide an introduction for those unfamiliar with the technology. Included will be a comparison of with LEDs, highlighting the advantages and disadvantages that OLEDs offer, as well as what the future holds for this unique technology.

Learning Objectives

1. Attendees will learn how OLEDs function and the fundamental differences between OLED and LED technology
2. Performance comparisons between LEDs and OLED will be presented allowing attendees to plan where OLEDs could be an appropriate choice for future facilities projects
3. Understanding how OLEDs unique properties can change the design of facilities in terms of lighting
4. The aesthetic characteristics of OLEDs will be discussed, so that facilities managers can understand the appeal of the technology to architects and lighting designers.
Outline

- Introduction ï What are OLEDs
- Unique Features ï What makes OLEDs different from other light sources?
- Comparison ï Advantages and disadvantages of OLED and LED technologies
- Applications ï Examples of OLED design

Introduction

The Future — Expanded growth as costs come down

![OLED panels revenues for lighting applications (2012 – 2020)](image)

Source: Yole Development
Introduction

OLED Market Forecasts – Widely varying projections

- Lux Research: $58M by 2020
- NanoMarkets: $1.4B by 2019
- UBI Research: $4.7B by 2020

![OLED Lighting Market Graph](Source: UBI Research)

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Introduction

How do SSL devices produce light?

Bandgaps – Different gaps, different colors

For metals $E_g$ is small, for insulators $E_g$ is very large. Materials between these two extremes are known as semiconductors

$E_C$ - Bottom of Conduction Band

$E_V$ - Top of Valence Band

When electrons and holes combine, the resulting photon has a wavelength related to the bandgap energy given by $\lambda = \frac{1239}{E_g}$

Smaller bandgap ⇒ Lower energy ⇒ Longer wavelength photon ⇒ Red

Larger bandgap ⇒ Higher energy ⇒ Shorter wavelength photon ⇒ Blue
```
Introduction

How Does an LED Create White Light?

**Downconverting Phosphor**
- Blue LED + YAG  **Cool**
- Blue LED + YAG + Other phosphor (red, green, etc.)  **Warm**
- UV LED + Red phosphor + Green phosphor + Blue phosphor

*Convention Coating*

*Conformal Coating*

**Cool White LED Spectra**

- *Blue Die*
- *Yellow Phosphor*

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Introduction

What is an OLED?

A "layer cake" with a thickness less than that of a human hair

An OLED or organic light-emitting diode is a semiconductor device which consists of an electroluminescent organic layer(s) sandwiched between two electrodes, at least one of which is transparent.

The device is fabricated by sequentially depositing organic layers on a conducting substrate followed by another conducting electrode.

A common device structure comprises a glass substrate coated with indium tin oxide (ITO) as transparent anode and a thin, opaque metal film as cathode.

Typical layer separation is < 100 nm

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Introduction

What is an OLED?

The major elements of an OLED device consist of the following:

Å Substrate – the support material that forms the base of the OLED; it can be of glass, metal or plastic;

Å Backplane – the circuitry that provides the power that drives the OLED panel (simple for lighting, complex for displays);

Å Organic layers – the actual OLED materials; phosphorescent and fluorescent materials that convert electrical energy into visible light energy;

Å Encapsulation – the protective layers that prevent moisture and oxygen from contaminating the organic (light producing) layers of the OLED.

A Close-up View of an OLED

Diagram of a Bottom Emitting, Stacked OLED

- Electron Transport Layer
- Hole Blocking Layer
- Emission Layers
- Electron Blocking Layer
- Hole Transport Layer

ITO - Indium Tin Oxide layer forms a transparent electrode

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Introduction

OLED Configurations – Different structures for different applications

OLEDs can be configured as larger-area, more diffuse light sources, which may be more practical for general ambient lighting because the soft light can be viewed directly, with less need for shades, diffusers, lenses, louvers, or parabolic shells. The diffuse light from OLEDs allows them to be used very close to the task surface without creating glare for the user, which means that less total light can be used in order to achieve desired illuminance levels.

![OLED Device Structures](source: OLED Basics; US Department of Energy)

- **Single-stack OLED**: The simplest configuration, for low-cost manufacture.
- **Stacked (or tandem)**: A more complex structure that can magnify the brightness without increasing current density.
- **Striped OLED**: Requires patterning but allows for color tunability. Generally red-green-blue or blue-yellow stripes.

Introduction

Some OLED Terms

Å Small molecule OLEDs (SM-OLEDs)
- Molecule weight less than 1,000 g/mole
- Majority of today’s devices, high performance, generally deposited by vapor phase deposition

Å Large molecule OLEDs (P-OLEDs or Polymer OLEDs)
- Are solution processable (i.e. ink-jet printing and spin coating fabrication which could drastically reduce manufacturing cost)
- Still at the development stage

Å Fluorescent materials
- Last longer than phosphorescent materials
- Less efficient with a maximum internal quantum efficiency of 25%

Å Phosphorescent materials (PHOLED)
- More efficient with an internal quantum efficiency of up to 100%
- Lifetime shorter than fluorescent materials so most companies use hybrid
- Typically requires doping with rare earth heavy metals (usually iridium)
Introduction

Some OLED Terms — What does "gen" mean

“Gen” refers to the generation of manufacturing line which is based on size of glass panel which the line is capable of producing. Each generation is capable of producing larger and larger panels of glass. This brings down the cost of the substrate on which the OLED is manufactured.

<table>
<thead>
<tr>
<th>Generation</th>
<th>Dimensions (mm)</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tbody>
<tr>
<td>1 (AMO)</td>
<td>200 x 300</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>2</td>
<td>250 x 350</td>
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<tr>
<td>6</td>
<td>920 x 1,120</td>
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<td>7</td>
<td>1,120 x 1,320</td>
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<tr>
<td>8</td>
<td>1,320 x 1,600</td>
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<td>9</td>
<td>1,600 x 1,920</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<td>10</td>
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</table>

Source: CLSA Asia-Pacific Markets

Outline

Â Introduction — What are OLEDs
Â Unique Features – What makes OLEDs different from other light sources?
Â Comparison — Advantages and disadvantages of OLED and LED technologies
Â Applications — Examples of OLED design

Source: GE
Unique Features

History of OLED Development — Displays and some lighting

• 1950: Electrolumiance in organic materials is observed for the first time
• 1987: The world’s first OLED device is developed at Eastman Kodak
• 1998: Kodak and Sanyo show the world’s first AMOLED display
• 2009: LG buys Kodak OLED unit
• 2010: Sony stops XEL-1 OLED TV production
• 2010: DuPont develops new OLED printing technology, can print a 50” panel in less than two minutes
• 2011: Samsung announces they will invest $4.8 billion in OLED production in 2011
• 2011: Verbatim starts shipping color-tunable OLED lighting panels (VELVE)
• 2011: Panasonic develops the world’s most efficient white OLED (128 lm/W)
• 2012: The world’s first transparent OLED lighting panel now shipping from COMEDD
• 2013: NEC developed the world’s most efficient OLED lighting device (156 lm/W)
• 2014: LG shows 77” bendable OLED TV prototypes

Source: The OLED Handbook; Ron Mertins; 2014

Unique Features

Advantages of OLEDs

• Flat Form Factor
  - Emits light over entire surface; also allows for easy heat dissipation
• Flexibility
  - As encapsulation techniques improve, ability to use flexible substrates such as metal foils or plastic
• Color Tunability
  - Spectra depends on the emitter material; generally wider and more flat than that of inorganic LEDs
• Efficiency
  - Target for 2020 is 190 lumens/W
  - Very low luminaire efficiency losses
• Transparency
  - Transparent OLEDs can be made which emit light from both sides when on, and are see-through in their off state (using transparent electrodes & substrate materials)

Source: DuPont Displays
Unique Features

Flexibility

Source: Michael Hack, Universal Display Corporation

Unique Features

Transparency – Disappears when not in use

Source: Osram

Source: Universal Display Corporation

Source: Yuan-Sheng Tyan, Kodak
Unique Features

Color Tunability – Broad spectra

- Wide range of phosphors and fluorescent materials allows broader spectra than available with LED technology

- Layer geometry allows uniform mixing of colors without pixilization or color shadows that often occur when mixing LED colors

Unique Features

The Major Issues – Performance, cost and lifetime

- Trapping of light inside OLED layers
- Phosphorescent blue material does not match performance of red and green
  - Use of hybrid fluorescent blue and phosphorescent red and green
- Unlikely development of low cost, low resistance, transparent sheet conductors
  - Use of wire grids may eliminate this issue
- Encapsulation to avoid moisture contamination
- Low volume production means high cost
  - Cost reductions driven by display manufacturing which typically does not require the high light output, long lifetimes and high efficacy required for lighting
  - Initial luminaire may require tiling approach

Source: Yuan-Shong Tyan, Kodak
Unique Features
The Major Issues – Performance, cost and lifetime

<table>
<thead>
<tr>
<th>Issue</th>
<th>Problem</th>
<th>Solution</th>
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<tbody>
<tr>
<td>Efficacy</td>
<td>Some lab devices can compete with conventional technologies, early products have low efficacy</td>
<td>Work needed to develop efficient, long-lasting blue emitter; next generation products reaching levels that compete with conventional lighting sources</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Short lifetimes for blue materials; susceptibility to moisture intrusion</td>
<td>Work needed on high current density, more stable materials, better and low cost encapsulation</td>
</tr>
<tr>
<td>Light Output</td>
<td>Current OLED packages produce “dim” light</td>
<td>Work needed to improve light extraction, high current density</td>
</tr>
<tr>
<td>Cost</td>
<td>Too high; lower cost device and luminaire materials are needed</td>
<td>Infrastructure investment needed to develop commercial OLED products</td>
</tr>
<tr>
<td>Testing Standards</td>
<td>No standards presently available for testing OLED products</td>
<td>Need for reliable test methods standards to establish consistency and reduce uncertainty</td>
</tr>
</tbody>
</table>

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Source: GE
Comparison

OLED Different Shapes & Sizes – Up to 320 mm² in a single panel

Comparison

Glare Reduction – OLEDs offer a "softer" light output

The LED's point-source characteristic concentrates the light at the source which creates an intense beam which can cause glare when viewed directly.

The OLED's uniform light distribution spreads the light over the entire area of the panel creating a soft, glowing light source when viewed directly.
Comparison

Spectral Power Comparison – Less severe dip in the green

OLED spectral power distribution can be designed to more closely match natural sunlight that the corresponding LED spectrum.

Source: LG Chem

LED Green Gap

Comparison

Drivers – LED and OLED devices require different drivers

Å LEDs
  î Can use constant voltage or constant current

Å OLEDs
  î Require constant current only
    • Static resistance of OLED devices increases over time. If used with a constant voltage device, the drive current will decrease resulting in loss of light output.

OLED driven with constant voltage source

Note decrease in lumen depreciation over time for constant current case.

Source: Osram
Comparison

Drivers – OLED devices require constant current drivers

The light output of an OLED device is also much more sensitive to changes in voltage than current

Source: Osram

Comparison

Drivers – OLED characteristics

- The preferred method to dim OLEDs is by changing the DC amplitude of the drive current to avoid shortening OLED life
- The use of Pulse Width Modulation (PWM) dimming drivers will significantly shorten the life of the OLED device
- Due to the high capacitance of OLEDs, the driver should be designed to take that into account. Otherwise high current or voltage spikes may result on turn-on/turn-off or at edges of PWM signals
- Drivers for use with OLED devices should be designed to provide minimum ripple current, unlike LED drivers which often trade higher ripple current for lower cost

Source: Osram
Comparison

Efficacy – Targets for OLED devices

Comparison of OLED and LED Target Projections

OLED Efficacy Projections
(White Light Panels)

Solid-State Lighting R&D Plan, May 2015

LED Package Efficacy Projections
(Commercial Products)

Comparison

One Cost Advantage of OLEDs – Optics and thermal

OLED savings in these areas

Source: Manufacturing Roadmap Solid-State Lighting Research and Development; US Department of Energy, August 2014
Comparison

OLED Efficacy – DOE goals and present performance

<table>
<thead>
<tr>
<th>Metric</th>
<th>2014</th>
<th>2017</th>
<th>2020</th>
<th>Goal</th>
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<td>Peak Efficiency (lm/W)</td>
<td>60</td>
<td>125</td>
<td>160</td>
<td>130</td>
</tr>
<tr>
<td>Optical Efficiency of laminaire</td>
<td>100%</td>
<td>100%</td>
<td>50%</td>
<td>50%</td>
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<tr>
<td>Efficiency of Unit</td>
<td>85%</td>
<td>85%</td>
<td>50%</td>
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<tr>
<td>Total Efficiency from Device to Laminaire</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
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<tr>
<td>Resulting Laminaire Efficiency (lm/W)</td>
<td>51</td>
<td>100</td>
<td>130</td>
<td>150</td>
</tr>
</tbody>
</table>

DOE goals

Source: US Department of Energy
SSL R&D Plan, May 2015

Comparison of commercial versus lab performance

1. Commercial panel utilizing a hybrid triple stack with fluorescent blue emitters and phosphorescent red and green.
2. Commercial panel utilizing a hybrid 6-stage stack with fluorescent blue emitters and phosphorescent red and green.
3. Laboratory panel utilizing a double stack with all phosphorescent emitters.
4. Test panel utilizing a single stack with polymer/oligomer emitters.

Comparison

OLED Research Projects – Programs funded by the DOE

Source: US Department of Energy R&D Roadmap, May 2014
The DOE supports SSL R&D in partnership with industry, small business, and academia. Presently there is $50.9 in funding for the current solid-state lighting portfolio.

Approximately 29% of this funding is focused on OLED technology issues.

Comparison

DOE Research Grants – All aspects of solid-state lighting

DOE SSL R&D Active Portfolio

- LED Manufacturing: 43%
- OLED Manufacturing: 14%
- LED Core Technology: 13%
- OLED Core Technology: 8%
- LED Product Development: 15%
- OLED Product Development: 7%

Total: $50.9M

March 2015

Comparison

Comparing Approaches – Vacuum deposition versus ink jet

Two approaches to OLED manufacturing

Vacuum deposition

Ink jet printing

Source: Canon

Source: Aixtron

Source: Kateeva
GE and DuPont announced a pilot program a few years ago to integrate GE’s pre-pilot roll-to-roll manufacturing infrastructure with:

- High performance, solution processable materials
- Advanced device architectures
- Advanced encapsulation using ultra-high multilayer barrier films (alternate ceramic/plastic layers)

Goal: Eliminate differences in OLED performance between laboratory-scale batch process and pre-pilot production

Not much progress in the last few years

Comparison

Cost – Printable OLED Lighting

Not all programs are successful

Project announced for upstate NY

- Project partners: DOE, Universal Display Corporation, Moser Baer Technologies, NY’s Smart System Technology & Commercialization Center (STC)

Joint effort to design and set up nation’s first pilot production facility for OLED lighting panels

Facility was to provide prototype panels to U.S. luminaire manufacturers to incorporate into products

Funding fell through and the project did not progress

Located in Canandaigua, NY, the STC was to house two pilot phosphorescent OLED manufacturing lines.
Due to the high Index of Refraction of the semiconductor ($n_s$) as compared to the epoxy dome material ($n_e$), by Snell's law, photons exiting the active layer at angles greater than the escape cone angle $\theta_c$ will be reflected back into the semiconductor and will not exit the device.

Some device manufacturers cut the sides of the chips to provide better exit angles and extract more light while others rough the surfaces of the chips to create optical interfaces which can improve the overall light extraction. A third approach is to use what are known as photonic crystals to reduce certain propagation modes (reflected) and increase others (exiting).

**Comparison**

**Light extraction**

Light extraction is a problem with OLEDs as well as LEDs. In the case of OLEDs, the light gets trapped in the thin organic layers due to the high difference in refractive indices.

**OLED Issues – Light extraction**

Improved light extraction method
More light
More complex production $$$

Source: Kazuyuki Yamae, et al., Panasonic Corporation
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Majority of commercial investment in OLED technology has been focused on display applications – for example, Samsung has recently averaged about $5B per year.

Source: LG Electronics
Source: Samsung

LG plans to produce 600,000 OLED TVs (55", 65" and 77" during 2015
Applications

Human Psychology – How lighting affects our well-being

OLEDs have the potential advantages of non-glare illumination and warm color characteristics

Economics
- Installation
- Maintenance
- Operation
- Energy
- Environment

Architecture
- Form
- Composition
- Style
- Codes & Standards

Individual Well-Being
- Accessibility
- Activity
- Social & Communications
- Mood, Comfort
- Health & Safety
- Aesthetic judgment

Lighting Quality

OLEDs do not require heat sinks or large fixtures, they are more expensive, however

OLEDs allow designers new form factors that they have only begun to explore


Applications

Niche Products – New form factors but high cost

Â Offers Architects/Lighting Designers the ability to eliminate the distinction between light source and luminaire

Â Its creates a plane of light with no perceptible volume

Â Its form factor is very flexible allowing widely varying form factors and shapes
  ï Future flexible substrates will allow variation in shapes

Â Provides soft, glare-free illumination without requiring diffusers, baffles, etc.

Source: Acuity

Source: Acuity

Source: Novaled
Applications

Niche Products – New form factors but high cost

Source: Osram

Source: Philips Lumiblade

Source: Universal Display Corporation

Applications

Unique Characteristics – Allow unusual form factors for luminaires

Source: LG Chem
Applications

Unique Characteristics — Allow unusual form factors for luminaires

OLED Chandelier
Price: $9,990

Details:
- Finish: Brushed Aluminum
- Material: Aluminum
- Aluminum body
- Brushed Aluminum finish
- Ceiling canopy
- Four stems
- Dimmable with electronic low voltage (ELV) dimmer (not included)
- LED Average Rated Life: 16,000 hours
- LED Color Temperature: 4000K
- CRI: 82
- 2040 lumens
- UL Listed
- Made In China

Source: Modern Forms

Applications

Unique Characteristics — Allow unusual form factors for luminaires

Source: LG Chem

Source: Acuity Lighting

Source: Philips Lumiblade (Riva 1920)
Applications

Unique Characteristics – Allow unusual form factors for luminaires

Source: Blackbody (Astrom FIAMM)

Source: Acuity
Applications

Unique Characteristics – Allow unusual form factors for luminaires

(Right Figure) Waving your hand up and down in front of the sensor as well as forward and backward, changes the light level as well as on/off for the various OLED panels that make up the fixture

Applications

OLED Fixtures – A chandelier

This beauty can be yours for only $54,000

Fixture designed by Christopher Bauder
576 OLED panels
Applications

Are OLEDs Only For Multi-Millionaires?

Applications

The Answer is No – OLED fixtures showing up at big-box stores

Available now at a store near you

$299.00 each
Acutane Shards 2 Panel LED Square Light
Model: 4420
Available Stock: 30

$199.00 each
Acutane Shards 2 Panel LED Square Light
Model: 4420
Available Stock: 30

$199.00 each
Acutane Shards 2 Panel LED Square Light
Model: 4420
Available Stock: 30

$199.00 each
Acutane Shards 2 Panel LED Square Light
Model: 4420
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Photo Credit: ©John Sutton Photography 2011
Final Thoughts

Are OLEDs Ready for Prime Time – It depends

• OLEDs still have quite a ways to go to compete head to head with LED technology for many traditional lighting applications and may, in fact, never get there
• The unique characteristics of OLEDs fit quite nicely with how designers and architects think of lighting; less so for those whose first impulse is to pull out a light meter
• OLEDs can typically provide a broader spectrum than LEDs
• OLEDs naturally produce diffuse light; LEDs have to work at it
• OLED manufacturing cost remains one of the major hurdles to overcome for broader adoption of the technology
• Both OLEDs and LEDs experience cost benefits from their association with the TV/display industry
• OLEDs will have a place in tomorrow lighting landscape

Acknowledgement

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Thank You!

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Don't forget:
10:15 - 11:30 am Special Session: Life on the Rock
11:30 am - 4:00 pm NECA Show Hours