A Guided Tour of SSL Area
Light Sources – Past, Present and Future

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Learning objectives

1. Fundamental principles of luminescence
2. Technologies for area SSL sources
3. Metrics and how these technologies compare
4. What of applications they enable and how they will impact future luminaire design

Throughout this seminar, we’ll use symbols to call out key concepts and common threads.
Overview

- Why area light source (JF)
  - Introduction
  - Metrics

- SSL area sources and technologies (ML)
  - Basic Physics
  - Detailed examples
  - Summary

- Lighting Application (JF)

- Conclusions
Why area light source
Architecture: Smallwood, Reynolds, Stewart and Associates
Lighting: Terry Bell / CD+M Lighting Design Group, LLC
Photography: Paul Warchol
Architecture: Gensler
Lighting: Darrell Hawthorne / Architecture & Light
Photography: Nic Lehoux
Design Intent: Illuminate grand space using curved luminous surface to accentuate architecture

Luminaire: Wall-mounted indirect ceramic metal halide

Lamping: 2 – 400W ED28

Luminaire efficacy: 70 lm/W

Implementation: Each luminaire weighs over 60 lbs and requires 2 remote ballasts mounted in ventilated area
Design Intent: Provide visual hierarchy and orient patrons using large luminous surface and illuminated sculpture, both of which provide general illumination

Luminaire: 18’ dia custom pendant and concealed architectural cove lighting
Lamping: 42W Triple Tube CFL – 38 in pendant; 144 in cove
Luminaire efficacy: 70 lm/W
Implementation: 1200 lb custom luminaire in finely detailed and complex installation
**Design Intent:** Use floating luminous surface to provide comfortable and diffuse illumination while preserving visual rawness of the building infrastructure.

**Luminaire:** Pendant indirect-direct linear fluorescent

**Lamping:** 2 – T5HO per 4’

**Luminaire efficacy:** 76 lm/W

**Implementation:** Requires installation of floating ceiling clouds and independent seismic bracing of ceiling clouds and luminaires - while visual mass of luminaires is minimal, the practical solution compromises the design intent.
Why area light source

- We have illustrated a historical perspective of the desire for and implementation of area light sources using “virtual” approaches.

- Later we will explore how actual area light sources may be realized.

- But first let’s define how to evaluate these technologies.
Metrics

- Efficacy
- Lifetime
- Light quality
  - CRI (Ra and R9), CCT, Duv
  - Color consistency within the panel and as a function of viewing angle
  - Uniformity within the panel and panel-to-panel
  - Appearance/pixelation
Metrics

- **Form Factor**
  - Thickness
  - Size
  - Border width
- **Cost per area and per kilolumen**
- **Technology Maturity and Promise**
  - Industry participation
  - Manufacturing presence
  - Product/sample availability
  - Long-term projections and theoretical limits
- **Other**
  - Flexibility
  - Transparency
  - Off-state appearance
  - Robustness
  - Thermal
  - Driver
  - “Green”
SSL Area Sources and Technologies

- Basic physics – different kinds of “luminescence”
- SSL area sources and evaluation metrics
  - Thin film EL
  - Edge-lit LED flat panels
  - OLED
  - Micro-plasma
  - Printed Micro LED
  - Quantum Dot LED (QLED)
- Summary comparison
An excited particle (atom or molecule) can only lose its extra energy in a few ways:

- Generate heat
- Transfer the energy to another particle
- Break apart
- Emit light: luminescence

**Luminescence**

*The low-temperature emission of light (as by a chemical or physiological process)*

– Merriam-Webster Dictionary
Different Kinds of Luminescence

- Photoluminescence
  - The emitting specie is excited by high energy photons.

White Light
Uses rare-earth phosphors:
E.g., Tb, Ce:LaPO₄, Eu:Y₂O₃

Fluorescent Lamp
Rare Earth Elements
Different Kinds of Luminescence

- Photoluminescence
- Electroluminescence
  - The emitting specie is excited as the result of passing an electrical current or applying an electrical field.

Early pn junction LED

Phosphor converted LED:
Blue LED + yellow-green phosphor \((\text{Ce}:\text{Y}_3\text{Al}_5\text{O}_{12})\)
Different Kinds of Luminescence

- Photoluminescence
- Electroluminescence
- Cathodoluminescence
  - The emitting specie is excited by an electron beam.

RGB phosphors:
- $\text{Y}_2\text{O}_2\text{S}:\text{Eu}+\text{Fe}_2\text{O}_3$
- $\text{ZnS}:\text{Cu,Al}$
- $\text{ZnS}:\text{Ag+Co-on-Al}_2\text{O}_3$
Different Kinds of Luminescence

- Photoluminescence
- Electroluminescence
- Cathodoluminescence
- Chemiluminescence

  - Emission of light with limited heat, as the result of a chemical reaction.

---

NOT limited heat aka Combustion
Different Kinds of Luminescence

- Photoluminescence
- Electroluminescence
- Cathodoluminescence
- Chemiluminescence
- Other mechanisms
  - Radioluminescence: excitation by radiation (alpha, beta)
  - Sonoluminescence: excitation by sound (collapsing a bubble)
  - Bioluminescence: excitation by cellular activities
  - Triboluminescence: excitation by breaking bonds in a material

In the era of electric lighting, the dominant mechanisms are photo- and electro-luminescence.
Electroluminescent Panel

Electroluminescence

Field Driven

Current Driven

- DC EL
- AC EL
- LED
- OLED

- Essentially a parallel plate capacitor with a layer of phosphor in the middle
- AC voltage results in a sheet of charge “sloshing” back and forth exciting the phosphor layer which emits light.
Electroluminescent Panel – Properties

- Emission is from a typical SrS:Ce/ZnS:Mn phosphor. Duv is higher than optimal. Color rendering is very good.
- Luminance is dependent on the frequency of AC voltage.
- L₇₀ on the order of 1000 hrs. Luminance decay is exponential and a function of luminance.

Luminance 110 cd/m²
CCT 5813K
CIE (0.325, 0.353)
Duv 0.009
CRI Ra 91, R9 62
Electroluminescent Panel – Pros and Cons

- **Pros**
  - Large area, flexible
  - Inexpensive
  - Mechanically robust

- **Cons**
  - Low luminance/lifetime
  - Poor color quality for general lighting
Electroluminescent Panel – Application & Future

- Current Applications
  - Nightlight, egress lighting
  - Architainment
- Other EL applications
  - LCD backlight
  - TFEL displays
- Future for general lighting
  - Limited
Originated from LED backlight technology in LCD displays.

- Emission from LEDs at panel edge is coupled into the waveguide, propagates and is scattered by surface features (v-groove, microlens).
- Coupling efficiency (panel output/LED output) varies widely from 55-95%.
- Waveguide thickness varies from many millimeters to 250 microns.

*K. Drain, Rambus, DOE SSL R&D Workshop, Feb 2011*
Edge-Lit LED Flat Panel – Properties

- Emission spectrum is by-and-large the same as the LEDs used.
  - It is possible to use both cool and warm white LEDs and have a CCT tunable source (e.g. LG Innotek), or to use RGB LEDs and perform color mixing within the waveguide.
  - Since tens or even hundreds LEDs may be used, tight binning of individual LEDs is not as critical to panel-to-panel color matching.

Example: Cree XP-G
One advantage of the microlens approach is the possibility to steer emission by change profiles of the microlens.

Alone or in combination with additional optical films it’s possible to realize high angle cut-off for glare control and bat-wing distribution for indirect, volumetric lighting.

*K. Drain, Rambus, DOE SSL R&D Workshop, Feb 2011*
Edge-Lit LED Flat Panel– Design Possibilities

Kite, Peerless

GE

Rambus

Rambus
Edge-Lit LED Flat Panel – Pros and Cons

- **Pros**
  - Harness the rapid development of LEDs in both performance and cost.
  - Versatility in photometric distribution control
  - Possibility for curved surfaces

- **Cons**
  - Coupling efficiency around 60% for the most available architecture; need many “tricks” for the best coupling efficiency.
  - Border width, WGP thickness vs. performance trade-off
  - Flexible WGP performance uncertain
  - Possible to do truly arbitrary shapes?

- **Future**
  - Certainly will be a major area source technology
OLEDs are planar two-terminal devices. Upon application of a current, electrons and holes recombine inside the device to emit light (electroluminescence).
Organic Light Emitting Diode (OLED)

- They are called “organic” because the key functional layers are made of complex carbon containing molecules.
- The active layers are less than 1 micron thick.
- They are inherently large area devices and can be made flexible.
OLED – Properties

- Typical white OLEDs today have emission from red, green and blue molecules in the same device rather than blue + phosphor in LEDs.
- Emission spectra from organic molecules are broad. High CRI, Ra, R9 > 90 possible.
- *Phosphorescent* OLEDs enable higher efficacy. State-of-art is 60 lm/W, $L_{70} = 15K$ hrs @ 3000 cd/m$^2$ (LG Chem).
A Little Clarification

- Phosphorescent, Phosphorescence
  - Originally refers to a type of photoluminescence where the material does not immediately re-emit light, as opposed to fluorescence.
  - Emission comes from a spin-forbidden (triplet) state.
  - OLEDs do not contain any phosphor.

- Phosphor
  - Emits light when irradiated by high-energy electromagnetic radiation or particle radiation
  - Includes both phosphorescent and fluorescent materials.
  - Often transition metal or rare earth metal compounds

- Phosphorus
  - The chemical element named for its light emitting behavior, emits light from chemiluminescence, not phosphorescence.
  - Phosphorus is not used as a phosphor in lighting and displays.
# OLED vs LED – Luminaire Efficacy Projections

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th></th>
<th>2015</th>
<th></th>
<th>2020</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>LED</td>
<td>Edge-lit LED</td>
<td>OLED</td>
<td>LED</td>
<td>Edge-lit LED</td>
<td>OLED</td>
</tr>
<tr>
<td>Package/Panel lm/W</td>
<td>141</td>
<td>141</td>
<td>60-80</td>
<td>202</td>
<td>202</td>
<td>125</td>
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<tr>
<td>Driver Efficiency</td>
<td>86%</td>
<td>86%</td>
<td>86%</td>
<td>89%</td>
<td>89%</td>
<td>89%</td>
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<tr>
<td>Thermal Efficiency</td>
<td>86%</td>
<td>86%</td>
<td>100%</td>
<td>88%</td>
<td>88%</td>
<td>100%</td>
</tr>
<tr>
<td>Optical Efficiency</td>
<td>86%</td>
<td>79%</td>
<td>100%</td>
<td>89%</td>
<td>83%</td>
<td>100%</td>
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<tr>
<td>Luminaire lm/W</td>
<td>90</td>
<td>82</td>
<td>52-69</td>
<td>141</td>
<td>131</td>
<td>111</td>
</tr>
</tbody>
</table>

- Based on DOE and ABL projections.
- Current density of 35 A/cm² assumed for LEDs. Higher current density results in lower efficacy before 2020. LED package listed for 25°C.
- *Today*, edge-lit panels typically don’t use the highest efficacy LEDs.

*Lu et al., DOE SSL R&D Workshop, Jan 2012*
OLED Luminaires – New Design Possibilities

Kindred, Winona Lighting

Airbesc, Osram

Victory, Liternity

Blackbody

O’Leaf, Philips
Other Unique Aspects of OLEDs

- Clean edge, thin
  
  Panasonic

- Full color tuning in a flat panel package
  
  Mitsubishi Chemical/Verbatim

- Flexible
  
  GE, Konica Minolta

- Arbitrary shapes
  
  Philips

- Transparent
  
  Novaled
OLEDs – Pros and Cons

- **Pros**
  - Outstanding quality of light
  - Thin form factor (<2 mm), thin border width (<5 mm)
  - Low temperature operation (<10°C above ambient)
  - Transparent, flexible OLEDs, arbitrary shapes possible
  - Long-term efficacy projected to match edge-lit LED
  - Potential for printing process

- **Cons**
  - Cost (needs volume)
  - Lifetime (3x increase desired; will improve naturally with efficacy)

- **Future**
  - OLEDs will be another major area light source technology besides edge-lit LED
Comparison of Area Source Technologies – Past and Present

<table>
<thead>
<tr>
<th></th>
<th>Efficacy</th>
<th>Lifetime</th>
<th>Light Quality</th>
<th>Form Factor</th>
<th>Cost</th>
<th>Tech Promise</th>
<th>Other</th>
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</thead>
<tbody>
<tr>
<td>EL Panel</td>
<td>★★★★★</td>
<td>★★</td>
<td>★★</td>
<td>★★★★★</td>
<td>★★★</td>
<td>★</td>
<td>★★</td>
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<tr>
<td>Edge-Lit LED</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★★★</td>
<td>★★★</td>
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<tr>
<td>OLED</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★★</td>
<td>★★★★★</td>
<td>★★</td>
<td>★★★★★</td>
<td>★★★★</td>
</tr>
</tbody>
</table>

★Poor ★★Fair ★★★Good ★★★★★Excellent
Microplasma Lighting

- Plasma is a state of matter similar to gas in which a certain portion of the particles are ionized.

- Electrons collide with plasma inside the cavity → UV light → strikes the phosphor coating → white light (photoluminescence)

Cf. plasma display panel (PDP)
Microplasma Lighting – Characteristics

- Max luminance: 8000 cd/m²
- CRI: 80-85
- Lifetime: L₇₀ 50K hrs
- Efficacy: 30-40 lm/W currently, expected to increase to 60 lm/W, theoretical limit > 100 lm/W
- Leverages existing manufacturing know-how
- Estimated purchase cost for 12”x12” panel: $100-200

Source: Eden Park Illumination
Printed Micro LEDs

- Problem to be solved: How to make a large-area, flexible light source without making an OLED?

- Solution: start with a wafer of inorganic LEDs, break into tiny individual LEDs, then disperse onto a sheet and make electrical connections.

- Two teams using the same general approach
  - NthDegree Technologies: “Printed Solid State Lighting”
  - Prof. Ralph Nuzzo’s group, University of Illinois: “Printing Solid Inks”
LEDs the size of an ink particle (27 micrometers) forms a suspension.
- This “ink” is coated onto a plastic substrate.
  - Think of the LEDs as a large number of loaded dice thrown on to a surface – enough will land the right way.
- Fast and low-cost, although not necessarily the highest performance
Printed Micro LEDs – 1st Approach

2’ x 4’ Replacement
1.75” thick with power supply

Edison Replacement

NthDegree Technologies
Printed Micro LEDs – 2nd Approach

- LEDs on wafer
- Ohmic Contact and Trench Formation & KOH Undercut
- Lift off with PDMS stamp
- "Step & Repeat" "Areal Expansion"
- Print to secondary substrate

- Same performance as wafer based LEDs
- Process intensive

Source: Prof. Nuzzo, Univ. of Illinois
Printed Micro LEDs – 2nd Approach

Lit micro LED array

Lit micro LED array w/ diffuser

On transparent and flexible substrate

Overlay a dollar bill

Source: Prof. Nuzzo, Univ. of Illinois
Quantum Dot LED (QLED)

Quantum dots are functionalized nano particles. Three parts of QDs are engineered to optimize performance:

- **Core**: Binary or ternary semiconductors, e.g., CdSe, InP; size and composition determines color
- **Shell**: Wider bandgap semiconductor; enhances efficiency and stability
- **Caps or Ligands**: Typically aliphatic organics; passivates & functionalizes surface; allows solution process

Source: QDVision
Quantum Dots as Phosphor

Photoluminescence of QDs in solution

Narrow band emission tunable throughout the visible range

Nexxus Lighting PAR lamp with QD optic for red shift and CRI enhancement

Source: QDVision
QD Light Emitting Diodes (QLEDs)

- The basic QLED structure is very similar to that of an OLED.
- QLEDs can be thought of as solution processed OLEDs with QDs as emitters.
- Red QLED performance approaches the best red OLEDs.

Source: Nature Materials
Comparison of Area Source Technologies – Future

<table>
<thead>
<tr>
<th></th>
<th>Efficacy</th>
<th>Lifetime</th>
<th>Light Quality</th>
<th>Form Factor</th>
<th>Cost</th>
<th>Tech Promise</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ plasma</td>
<td>★★★★</td>
<td>★★★★★</td>
<td>★★★</td>
<td>★★</td>
<td>★★★★</td>
<td>★★</td>
<td>★</td>
</tr>
<tr>
<td>μ Printed LED1</td>
<td>★★</td>
<td>★★★</td>
<td>★★</td>
<td>★★★★</td>
<td>★★★</td>
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<tr>
<td>μ Printed LED2</td>
<td>★★★★</td>
<td>★★★★</td>
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<td>★★★★</td>
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<td>QLED</td>
<td>★★★</td>
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<td>★★★★</td>
<td>★★★</td>
<td>★★★★</td>
<td>★★★</td>
</tr>
</tbody>
</table>

★Poor ★★Fair ★★★Good ★★★★★Excellent
Lighting and Display

- Many light sources and display devices operate on the same physical principles.

- Displays commands a higher price ($/in^2) and tend to be the preferred vehicle for new technologies.
  - Displays need RGB pixelation addressing.
  - Displays need saturated RGB; general lighting needs color points along the Planckian locus, with good color rendering.
  - One or two technologies tend to dominate displays. Many different lighting technologies tend to co-exist.

- As competition in displays drives down margins, many display makers are looking to SSL as an area of expansion – *lighting is no longer in the shadow of displays!*
Lighting Application
Using Area Light Sources

Rapt Studio

LG Chem
# How Much Do I Need?

<table>
<thead>
<tr>
<th>Baseline – Traditional Systems</th>
<th>2x4 fluorescent lensed troffer</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2x4 fluorescent parabolic troffer</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>2x4 fluorescent advanced troffer</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>Linear fluorescent indirect / direct</td>
<td>4%</td>
</tr>
<tr>
<td>Advanced Alternatives</td>
<td>2x4 LED advanced troffer</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>Fluorescent low ambient / task</td>
<td>4-10%</td>
</tr>
<tr>
<td>Area - Low</td>
<td>@ 1500 cd/m²</td>
<td>14%</td>
</tr>
<tr>
<td>Area - Med</td>
<td>@ 3000 cd/m²</td>
<td>7%</td>
</tr>
<tr>
<td>Area - High</td>
<td>@ 5000 cd/m²</td>
<td>4%</td>
</tr>
</tbody>
</table>

Ceiling Coverage = % of ceiling area obstructed by luminaire
There is no need to cover the whole ceiling
Familiar Form Factors

GE and Lunera
Familiar Form Factors
New Form Factors

This design demonstrates the unique character possible with area light sources.

The light is noble, pure, simple, honest.

LIGHT itself becomes the luminaire.

Luminaires connect with us emotionally by their design intent and beauty.

Panels: 60 lm/W panels, CRI>80, CCT 3500K, L₀=3000 cd/m², L₇₀ 15,000 hrs @ 3000 cd/m²

Luminaire: 5 panel module, 370 lm total, 7.3 W, 51 lm/W including driver and optical losses

Panels: 60 lm/W panels, CRI>80, CCT 3500K, L₀=3000 cd/m², L₇₀ 15,000 hrs @ 3000 cd/m²

Luminaire: 45 panels, 3382 lm total, 66 W total, 51 lm/W including driver loss

Acuity Brands
Photography: John Sutton 2011
New Form Factors
New Form Factors

This design evokes the connectivity and beautiful branching of a growing neuron.

Organic patterns form and flow gracefully through a space in unique and fluid motifs for close-to-ceiling applications.

Panels: 60 lm/W panels, CRI>80, CCT 3500K, $L_0=3000 \text{ cd/m}^2$, L70 15,000 hrs @ 3000 cd/m²

Tri Section: 24 panels, 1810 lm total, 35 W, 52 lm/W

Straight Section: 8 panels, 603 lm total, 12 W, 52 lm/W

Acuity Brands
Photography: John Sutton 2011
New Form Factors

Rambus

Acuity Brands
Photography: John Sutton 2011
New Metrics for Design

- Density of panels (3000 cd/m² example)
- Application efficiency

48 TRI sections
Ambient avg: 50 fc
Max / Min: 2.1:1
LPD: *1.05 W/ft² **0.79 W/ft²
# of 4” sq. panels: 0.72/ft²

50 TRI sections
Ambient avg: 53 fc
Max / Min: 2.6:1
LPD: *1.10 W/ft² **0.83 W/ft²
# of 4” sq. panels: 0.75/ft²

32 TRI + 22 STRAIGHT sections
Ambient avg: 43 fc
Max / Min: 4.9:1
LPD: *0.86 W/ft² **0.65 W/ft²
# of 4” sq. panels: 0.59/ft²

*60 lm/W
**80 lm/W
New Form Factors

~ 46 fc @ workstations

0.76 W/ft² @ 60 lm/W
0.57 W/sf @ 80 lm/W
0.45 W/sf @ 100 lm/W
Newer Concepts

33 fc @ reception desk
1.11 W/ft² @ 60 lm/W
A snapshot of a ballerina can be breathtaking, but witnessing her dance from beginning to end can touch our soul.

Acuity Brands
Newer Concepts

33 fc @ conference table
1.02 W/ft² @ 60 lm/W
Newer Concepts
This is just the beginning.
Conclusions

- Area light sources offer designers many opportunities for practicing the craft of architectural lighting.
- Old and new lighting technologies make flat panel sources practical to implement.
- A combination of medium luminance and small size panels offer the best design flexibility and application efficiency.
Please complete the course evaluation forms.

THANK YOU!