Reinventing Lighting

DOE SSL R&D Workshop
Jan. 27, 2015

John Edmond
Cree, Inc. Co-Founder and Director, Advanced Optoelectronics Technology
LEAD THE LED LIGHTING REVOLUTION to obsolete energy-inefficient lighting
Outline

- Fundamental Approach
- LED Milestones
- LED Chips and Components
- The light bulb: Edison to LEDs
- LED General Lighting
- End Results: Jobs!
Outline

• Fundamental Approach

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• LED Chips and Components

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Vertical Integration

**Approach**
- Innovation and Technology drive actions at every level
- Vertical Integration enables end-to-end optimization

**Result**
- Best in class performance and cost
- Best customer experience and Quality
Innovation requires a lot of work and R&D dollars.
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LED Milestones Timeline

1987

Cree founded NC State Univ.
Started with 6-Guys 1987
LED Milestones Timeline

1987
- Cree founded

1989
- Commercialized first blue LED SiC/SiC
First RGB Full Color Display (1993)
LED Milestones Timeline

1987
- Cree founded
- SiC/GaN Blue LEDs designed into VW Dashboard

1989
- DOE "White LED Dev. for General Illumination Applications" (10/00-10/04)

1995
- Commercialized first blue LED SiC/SiC
- First XBright® LED power chip

2002
- DOE "High Efficiency LED Lamp for Solid-State Lighting" (10/03-12/06)

2004
- First XLamp LEDs brought to market 50 LPW

2006
- First "Lighting-Class" LED components 100 LPW
- DOE "An Integrated Solid-State LED Luminaire for General Lighting" (10/06-9/08)

2007
- First commercially-viable LED downlight and LED streetlight

2009
- First commercially-viable LED PAR Lamp

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**LED Milestones Timeline**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>First 100 LPW LED parking/canopy fixture.</td>
<td>Commercially available white LEDs exceed 150 LPW.</td>
</tr>
<tr>
<td>2011</td>
<td>First commercially-viable LED troffer.</td>
<td>Commercially available white LEDs exceed 200 LPW MKR.</td>
</tr>
<tr>
<td>2012</td>
<td>Cree introduces first sub $200 LED streetlight.</td>
<td>Cree introduces the Cree LED Bulb.</td>
</tr>
<tr>
<td>2013</td>
<td>Cree takes control of controls with SmartCast™ Technology.</td>
<td>Cree is the 1st to break the 300 LPW barrier.</td>
</tr>
</tbody>
</table>

Cree is the 1st to break the 300 LPW barrier.
DOE investments in SSL R&D: high impact

• **10** completed DOE-funded Cree projects since 2000
• **Joint investment:** $19.2MM DOE funding synergistic with $7.5MM Cree cost share

High *success* rate of projects + Major Cree IR&D *investment* = Rapid transition to *products*

• Proliferation into all levels of the Cree SSL value chain

DOE spin-outs: LRP-38
DOE spin-outs “inside”: AR24, LM16, A bulbs

DOE spin-outs: XQ, XB-G/E, MPL-TW
DOE spin-outs “inside”: XR-E, XP, XTE-HV

DOE spin-outs: EZ gen I, II
XBright, XThin
### Ongoing DOE-funded Programs @ Cree

<table>
<thead>
<tr>
<th>Project</th>
<th>DOE / Cree Investment</th>
<th>Primary Focus Areas</th>
</tr>
</thead>
</table>
| “Scalable Light Module For Low-cost, High-efficiency LED Luminaires”   | $2.35M / $2.35M       | • Compact, high-efficacy, high-CRI LEDs  
• Modular low-profile, cost-effective optical elements with high optical efficiency |
| (8/13-7/15)                                                            |                       |                                                                                     |
| “Scalable, Economical Fabrication Processes For Ultra-compact Warm-white LEDs” | $1.49M / $497K        | • Ultra-compact LED (UCL) packages via new scalable, low-cost fabrication processes  |
| (8/14-1/16)                                                            |                       |                                                                                     |
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• Fundamental Approach

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• **LED Chips and Components**

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• End Results: Jobs!
Start with a III-Nitride chip

- **SiC ($E_g=3.2eV$)**
  - Vertical current flow
    - (+) top, (-) bottom

- **SiC Flip**
  - Lateral current flow
    - (+) and (-) on bottom

- **EZ/WZ**
  - Vertical current flow
    - (-) top, (+) bottom
Chip Architecture Features

- A photon is a terrible thing to waste...
  - Surface Features
  - Beveled saw cuts (SiC)
  - Internal mirrors
  - Flip-chip

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State-of-the-art Blue Chip Performance

447 nm, $T_j \approx 25^\circ C$

Radiant Flux (mW) vs. Current (mA) graph showing:
- 82% efficiency at 822 mW for a current of 782 mA
- 79% efficiency at 350 mA current

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LED Chip & Component Toolbox

- Lenses: Glass, silicone, none
- Lead frames, molded plastic bodies, ceramic substrates, hybrids
- LP/MP/HP/COB
- HD arrays
- Modules
- CRI, spectral modifications
- BSY+R (TrueWhite™)
- High voltage topologies
- Chips:
  - Single, multiple
  - SiC, sapphire
  - tiny ↔ largest in the industry
  - Brightest epi (lm/mm²)
  - Price/performance for any application
- Shipping hundreds of millions of units per month
Continuous Improvement in LPW

- **HID**: 120 LPW
- **Fluorescent**: 100 LPW
- **CFL**: 80 LPW
- **LED**: 60 LPW
- **Incandescent**: 40 LPW

**R&D Capability**
- 2003: 131 LPW
- 2005: 161 LPW
- 2008: 186 LPW
- 2011: 208 LPW
- 2013: 254 LPW
- 2014: 303 LPW

**High Volume Production**
- 2008: 3 yrs
- 2010: XP-G
- 2012: XM-L
- 2013: MK-R
- 2014: XP-L

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XLAMP PLATFORM

SC5 Platform
*Lowers system cost

SC3 and HD Platforms

2015

XP-G2

2012

XM-L

2009

Better Performance

Lower Cost

Lumens

Cost*

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Lighting Design Philosophy: LEDs or Applications First?

“LEDs then Application”

“Application then LEDs”
SC5 Technology Platform

Extreme High Power LEDs: XHP50 & XHP70

<table>
<thead>
<tr>
<th>XLamp XHP50</th>
<th>XLamp XHP70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footprint: 5.0 x 5.0 mm</td>
<td>Footprint: 7.0 x 7.0 mm</td>
</tr>
<tr>
<td>Max Power: 20W</td>
<td>Max Power: 30W</td>
</tr>
</tbody>
</table>

XHP Redefines High Power Lumen Density & Reliability to Lower System Cost

- **Double the lumens**: fewer LEDs & optics required
- **Radical system size reduction**: smaller chassis/heat sink
- **Improved long-term reliability**: reduce heat sink, not lifetime

<table>
<thead>
<tr>
<th>Lighting Apps</th>
<th>Non-Directional</th>
<th>Directional</th>
<th>Downlight</th>
<th>Linear</th>
<th>Outdoor/High Bay</th>
<th>Portable</th>
</tr>
</thead>
</table>
System Value of Lumen Density & Reliability

100W PAR38 Design Example
900 lumens, 40° beam, 1900 cd

- Smaller PCB: Fewer LEDs
- Smaller optic: Best LED lumen density
- Fewer LEDs: Better lumen maintenance
- Smaller heat sink: Better reliability at high temperature

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SC5 Value: Cree Lighting High Bay Luminaire

26,000 lm
12 CXA2530 LEDs
238 W
110 LPW
Tsp = 105 C

42,500 lm
54 XHP50 LEDs
404 W
105 LPW
Tsp = 125 C

46,200 lm
72 XHP50 LEDs
398 W
116 LPW
Tsp = 125 C
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…A Brief History of “Modern” Lighting

- **1783** Argand Oil Lamp
- **1810** Gas Lamp
- **1826** Limelight
- **1879** Edison Light Bulb
- **1938** Fluorescent Tube

- Current lighting technology is ~ 100 years old!
- It’s time for some innovation, ie LEDs!!

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Regarding Edison’s competition
- “gas lighting is (1) almost entirely heat and only incidentally a little light, (2) not to mention evil and a vile poison”

- Incandescents meet criteria 1
- Fluorescents meet criteria 2

The solution to both is LEDs!
Consumer - Some A19 Bulbs non-Cree

3M A19 Lamp
- 800 lm, 3000K, omni-directional
- Retail: $19 at Walmart
- Assembled in USA (Minnesota)

Best Buy Insignia A19 Lamp
- 450/800 lm, 3000K, omni-directional
- Retail: $14/$17
- Weight: 100g

GE A19 Lamp
- 450/800 lm, 3000K, omni-directional
- Retail: $15/$20
- Weight: 100g

Philips A19 Lamp
- 450/800/1100/1600 lm
- 2700 K, omni-directional
- Retail: $12/15/20/24

Target bulb segment
- 40W/60W/75W/100W+
  Omni-directional
- ANSI form factor bulb
- Light weight (~110g)
- Low Cost
Cree A19 LED Bulb

- Non-weird Shape
- Non-weird Color
- Pays for itself

$9.97 $7.97
CREE THE BIGGEST THING SINCE THE LIGHT BULB.™
Exclusively at The Home Depot

Backed by our 10-year warranty.
Built to last and last.

Up to 25,000 hours of beautiful energy efficient light.

Uses up to 85% less energy.

Designed and built in the USA.

NEW LOWER PRICE

$56.82
Was $77.82 Save 27%
Cree 60W Equivalent Soft White (2700K) A19 Dimmable LED Light Bulb (6-Pack)
Model # BA19-08027OMF-12DE26-2U100

$69.88
Cree 65W Equivalent Soft White (2700K) BR30 Dimmable LED Flood Light Bulb (4-Pack)
Model # BBR30-06527FLF-12DE26-1U100

$21.97
Cree 30/60/100W Equivalent Soft White (2700K) 3-Way A21 LED Light Bulb
Model # BA21-16027OMF-12WE26-1U100

$71.91
Cree 90W Equivalent Bright White (3000K) PAR38 47 Degree Flood Dimmable LED Light Bulb (3-Pack)
Model # BPAR38-1503047T-12DE26-1U100
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Figures of Merit For General Lighting

- **Correlated Color Temperature (CCT)**
  - The “shade” of white from yellowish (warm) to bluish (cool)

- **Color Rendering Index (CRI)**
  - How “true” object colors appear under “white” illumination
    - By definition CRI=100 for incandescent illumination

- **Vividness**
  - Color saturation relative to the blackbody

- **Lumens**
  - Brightness of a light source

- **Lumens/W**
  - How bright the light is divided by the power to create it i.e., efficiency of the light source
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Common Warm and Cool Sources

Color Temperature

Color Temperature Scale (°K)

1500  2000  2500  3000  3500  4000  4500  5000  5500  6000  6500

warm

- Halogen 3000°K
- Standard Incandescent 2700°K
- Neutral White 3500°K

cool

- Cool White Fluorescent 4200°K
- Daylight Metal Halide 5500°K

LED Approach

440-460 nm blue

+ or +

Nitride-based red phosphor + Red LED

Yttrium or lutetium aluminum garnet Yellow-green down conversion

Cree TrueWhite™
Figures of Merit For Lighting

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CRI Referenced to 14 Major Color Palettes
Some Stuff Looks Good; Some Stuff, Not-so-much…

CRI = 85  CRI = 78

Na Vapor Lamp

CRI = 65  CRI = 22
Why Your Customer Cares about #9

CFL
$R_9 = 0$

[It’s What’s For Dinner]

Cree TrueWhite™
$R_9 = 90$
Figures of Merit For Lighting

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“Color Quality” has been measured by CRI: “Fidelity”
- color *resemblance* to the blackbody

But color quality has a 2nd attribute: “Vividness”
- color *saturation* relative to the blackbody

Right-hand side is clearly better: but is this fidelity, or is it saturation?

In the past fidelity and vividness both increased with CRI, but SSL technology is changing

New opportunity: more vivid light sources give customers a choice
Higher Vividness is Sometimes Preferred

**NIST studies (Yoshi Ohno)**
- For colorful objects, people prefer more vivid light sources than CRI predicts

*CRI 94*

*This looks better (for most people)*

*CRI 78*

*Yoshi Ohno, “Latest Research and Standardization on Chromaticity & Color Quality of LED lighting,” SSL China, Nov 2014*
Color Quality Beyond CRI is Here Today

- True White® has higher vividness AND high fidelity:
  - >120 lm/W Product
  - 200 LPW R&D

- Technology can be optimized still further
More Can Be Done

- Increase Vividness via narrow spectral components
  - Other LED colors
  - New Phosphors

- Need to open up our color quality definitions to capture higher vividness than in the past
  - Ex: 90 CRI rules could hold back color quality as vividness increases
  - Current NIST and IES Color Quality Task Force efforts are a good start
Figures of Merit For Lighting

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Real LED Levels of Performance (Current)

Just like traditional lamps, LEDs have losses beyond the boiler plate data sheet specs...

...but the source of losses are somewhat different:

- Thermal (also a source of Lumen Depreciation)
- Optical (lenses, etc.)
- Driver (electrical losses in power conversion and dimming)

For blue + phos

<table>
<thead>
<tr>
<th></th>
<th>6000K</th>
<th>4100K</th>
<th>3500K</th>
<th>2700K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Sheet LPW</td>
<td>200</td>
<td>180</td>
<td>160</td>
<td>140</td>
</tr>
<tr>
<td>Typical Thermal Loss</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Typical Optical Loss</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Typical Driver Loss</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td>Achievable LPW</td>
<td>138</td>
<td>124</td>
<td>110</td>
<td>96</td>
</tr>
<tr>
<td>CRI</td>
<td>~75</td>
<td>~80</td>
<td>~82</td>
<td>~83</td>
</tr>
</tbody>
</table>

* Typical with average/good design practices

Note: Does not include Cree’s BSY + Red Technology
Projected LED Levels of Performance (2017)

Up 25% over next 3 years

<table>
<thead>
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<tbody>
<tr>
<td>Data Sheet LPW</td>
<td>250</td>
<td>225</td>
<td>200</td>
<td>175</td>
</tr>
<tr>
<td>Typical Thermal Loss</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Typical Optical Loss</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Typical Driver Loss</td>
<td>8%</td>
<td>8%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>Achievable LPW</td>
<td>208</td>
<td>187</td>
<td>166</td>
<td>145</td>
</tr>
<tr>
<td>CRI</td>
<td>~75</td>
<td>~80</td>
<td>~82</td>
<td>~83</td>
</tr>
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</table>

* State-of-the-art

- LEDs will be the most efficient mainstream light source available
  - >185 delivered LPW roadway light possible (4100K)
  - Indoor fixtures >145 LPW (wall-plug)
Cree’s world-class LED luminaires offer proven performance, style and affordability.
Cree TrueWhite® Technology Advantage

Color Mixing & Tuning

Patented mixing of LEDs delivers an improved visual environment using significantly less energy than traditional lighting technologies.
BEFORE – 6-LAMP T8

Quantity: 34
Total Watts: 6,120

AFTER – CS18™ LED

Quantity: 38
Total watts: 2,660

Payback Just Over
8 Months

Total Lifetime Savings:
$28,155 (50K Hrs)

Improved Vertical Illumination
and Color Quality

56% LESS
2 x 4 Troffers

Courtyard by Marriott
Louisville, KY

Balanced illumination from the CR troffer provides:

• Improved lighting quality: no harsh contrast; soft shadows

• Creating a mix of light to walls, partitions, vertical and horizontal work surfaces can increase the perceived light level and improve visual comfort!
ZR HE – 150 LPW 90 CRI 4000 Lumen Fixture !!!

- Cree TrueWhite® Technology
- Delivered Light Output: 3200, 4000 lumens
- Input Power: 21 to 44 watts
- LPW: 90-150
- CRI: 90
- CCT: 3500K, 4000K
- Input Voltage: 120-277 VAC
- Lifetime: Designed to last up to 75,000 hours (standard) and 100,000 hours (HE)
- 10-year limited warranty
- Mounting: Recessed

Applications
- Petroleum & Convenience Lighting
- Airport Lighting
- Auto Dealership Lighting
- Corporate Campus Lighting
- Education Facilities Lighting
- Government Facilities Lighting
- Healthcare Facilities Lighting
- Municipal Lighting
- Recreation & Public Venue Lighting
- Restaurant & Hotel Lighting
- Retail & Grocery Lighting
BEFORE - HID
19.1kW

AFTER - LED
6.5kW

Edgewater Marketplace - Edgewater, CO

Cree Edge™ Area Square

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$225,000 in Annual Energy and Maintenance Savings!
(1,100 luminaires)

BEFORE - HPS
400W

AFTER - LED
150 & 200W
LEDway® and XSP Street Light

Los Angeles, CA (2008-2012)

BEFORE - HPS

AFTER - LED

$10,000,000 in Annual Energy and Maintenance Savings!

63% LESS

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Traditional Post-Top LED Upgrade Kit

State Street
Racine, WI

LED Upgrade Kits for:
• Holophane®
  – Esplanade® Teardrop
  – Granville Acorn
  – Washington Post-Lite® Acorn
• King® Luminaire
  Washington Acorn
• Lumec® New
  Westminster Globe
Cree Edge™ Surface Mount Canopy

Richlands Station
Queensland, Aus.

- Modern look
- Excellent vertical light for pedestrians
- One-for-one replacement is a popular option
- Wide range of optics and lumen outputs
304 Series™ Parking Structure

Advocate Brommen
Normal, IL

Typical installation using no controls
• 2.4 year payback
• $405K lifetime savings*

Typical installation using occupancy sensors
• 2.3 year payback
• $516K lifetime savings*
Cree CPY250™ Surface Mount Canopy

Raleigh, NC
Super Bowl 2015

Ephesus Lighting
Powered by Cree® LEDs
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• End Results: Jobs!
Cree Company Overview

GLOBAL SCALE

- 28 global locations
- 7,100 employees

CREE FACTS

Fiscal 2014 Revenues ............... $1.6B
June 2014 Cash & Investments ...... >$1.2B
Long-term Debt ...................... 0
A Global Company

R&D
• Durham, NC
• Research Triangle, NC
• Racine, WI
• Santa Barbara, CA
• Florence, Italy
• Hong Kong

Manufacturing & Distribution
• North Carolina, USA
• Wisconsin, USA
• Italy
• China
• Canada
• UAE
• Australia

Sales
• USA
• Canada
• Mexico
• Germany
• France
• Italy
• Turkey
• UK
• China
• Singapore
• Japan
• Taiwan
• South Korea
• Russia
• UAE
• India
• Africa
• Chile
• Guatemala
• Australia
• New Zealand
• Panama
• Columbia
• Brazil

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Track Record of Growth

Revenue ($ Millions)

CAGR > 20%

Geographic Mix FY14

- North America: 49%
- China: 27%
- Europe: 9%
- Asia (ex. China): 10%
- ROW: 5%

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Cree and SSL are Making a Difference

• Leader in Creating and Growing an LED Lighting Industry

• Thousands of good-pay jobs created

• Thank you DOE for your support along the way