Evolution of Lighting
A fundamental need & technology

- Nuclear reaction
- Chemical reaction (combustion)
- Resistive heating (incandescent)
- Gas discharge (fluorescent, sodium vapor)
- Electroluminescence (light emitting diode)
Opportunity by market segment
Penetration of LED versus traditional light sources accelerating

- Rapidly growing **Illumination** market with significant upside through 2015+
- LED penetration in **Display** happening now across all applications
- **Automotive** growing steadily
- Camera **Flash** becoming fully captured by power LEDs
LED manufacturing (very simplified)

Epitaxy
- InGaN epitaxial growth on a sapphire substrate

Wafer/Die Fab
- Wafer processing (lithography, die structure, etc...)

Packaging
- Phosphor application
- LED packaging
- Test and ship

Phosphor
- Phosphor research and technology
Following a charted path?
First to 6” production benefits

• Realized improvements in...
  – Capacity and Productivity
  – Capability (Equipment)
  – Yield
The (key) benefit

DL H/C – 3” or Equivalent

Last 2 Quarters of 3” Mfg (mix)

150mm Mfg Only Starting 2012

150mm LED wafer
~16kmm²

Relative Manufacturing Cost (including volume)

Last 2 Quarters of 3” Mfg (mix)

150mm Mfg Only Starting 2012
New capabilities
For high defect, transparent substrates

- DOE collaboration with KLA Tencor on Candela 8620 during our 6” transition
- Develop high capability (defect sensitivity and discrimination)
- Track defects from substrate into epitaxy
- Improved 6” wafer quality at three sapphire suppliers

<table>
<thead>
<tr>
<th>Supplier A</th>
<th>Supplier B</th>
<th>Supplier C</th>
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<td>8620</td>
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<td>CS20</td>
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Increased sensitivity for defects on bare sapphire wafers

Sapphire improvement
Defects that matter
Next moves for substrates?

• Substrate materials
  – Sapphire: Dominant, current substrate cost for larger sizes
  – Silicon: Manufacturing and performance
  – GaN on GaN: Cost and value proposition
  – SiC: Single LED user with captive source

• Substrate size roadmap
  – 150mm: High-capability fab tools, SEMI wafer standard, real net cost advantage that continues to grow
  – 200mm: 1.8x die area, but same fab tool capability, forces new epi investment, no standards, high cost
  – One opinion: Players will make different moves depending on what cards they’re holding, how many chips they have, and what their game is...
Efficacy components and drivers

Continuing progress and potential in LED efficacy

1. Internal Quantum Efficiency
2. Extraction Efficiency
3. Electrical Efficiency
4. Wallplug efficiency
5. Conversion Efficiency

LUXEON T, 2mm², CCT = 3000K, CRI = 80
I_f = 350 mA, T_j = 85°C, \( \eta_{LE} = 119 \text{ lm/W} \)
Driven by system performance and cost
The game changes after “good enough” efficacy

Figure 3.7, Page 35, Solid-State Lighting Research Development Multi-Year Program Plan, DOE, Apr 2013
Figure 1-10, Page 24, Solid-State Lighting Research and Development: Manufacturing Roadmap, DOE, Sep 2013

|$30 | $15 | $8
8 oz | 6 oz | 3 oz
A means to an end
You’ve come a long way, epitaxy

• InGaN LED efficiency peaks at relatively low current densities
• Leading edge epitaxy
  – Lower cost
  – Higher efficiency
  – Broader efficiency peak
• Drive hard and/or throw epitaxy at the problem?
• Either way, it’s good to be the best
Architectures to go beyond 200 lm/W
How to continue Craford’s Law? How to add more value?

• Phosphor-converted LEDs flatten out at 200 lm/W
• Direct LEDs approach 266 lm/W, but require efficient yellow for high CRI
• A hybrid approach can deliver high efficacy and high CRI

From 2013 DOE SSL Multi-Year Program Plan

Philips TLED prototype:
• 200 lm/W
• CCT 3000-4000K
• CRI > 80, R9 > 20
Value from integration
Hybrid light engine with integrated color stabilization

- Easier calibration, better utilization
- More accurate sensing and control
- Compatible with existing single-channel drivers → simplification of system design

Value: Bringing control from the system level to the LED package
From need to desire: Irresistible light

LED applications increasingly driven by aesthetics & capability

• Controllable
• Connected
• Beautiful
• Will drive deeper L2 integration
• Supports renaissance of other 200mm Si components

“Lighting is not just about lighting anymore. The Internet of Things is coming and, not surprisingly, the IoT needs eyes and ears. Sensors, cameras, location data, user identification, and a host of other elements will let the IoT understand and respond. There are actually very few required categories of stuff in our modern built space. Walls, windows, roof, furnishings, HVAC, and lights. Which piece has electronics in it and becomes a natural host for those IoT eyes and ears?”

Form factors in the value chain to L2

epitaxy → waferfab → diefab → phosphor packaging → emitters → multi-die L2 emitters → L2 with integrated controls
Manufacturing architecture for L2 integration

• Delivering maximum value with smart driver & further integration into L2 implies customization and explodes the product mix

• Push differentiation to the latest possible part of the manufacturing flow

• Final product integration of building blocks to serve vast arrays of SKUs, close to the customer

• Highly-configurable manufacturing lines wherever product differentiation is unavoidable

• A flexible building block approach reaching back to the front-end

• Active device physics to manage changes and optimize use of distributions

• Fast cycle times up and down the line

• A nimble, efficient line employing well-understood building blocks with exquisite control
In 1873 - Alexander Graham Bell demonstrated the Telephone...
In 1876 – Thomas Edison patented the Electric Light Bulb...

Then later we got switchboards, direct dialing, digital, cordless....
Then later we got fluorescent, HID, halogen....

But, for 120 years, it was a box wired to a wall....and you could talk to folks who had another.....
But, for 130 years, it was a bulb wired to a wall-switch...

From the early 90’s till today......the Digital & Wireless Revolution has put one in every pocket.
It’s a computer, you type more messages than you call and you can talk to folks who don’t even have one....it is an essential lifestyle.

Today, we have digital control of a solid-state product... What now?
Thank you
Installed LED fab capacity by region

Installed capacity in wafers per month, 2” equivalents (Q4’11 forecast)

6.5M x 2” WPM = 400k x 8”
But mask count is low...4 to 5 layers per device,
Equivalent to 50-100k 8” WPM in 2011

Source: SEMI Opto/LED Fab Forecast March 2011
Trends in LED applications & architectures

**Was** –
Emerging products, mainly high power. Many remote phosphor.

**Is** –
Plethora of products, Hi, mid and low power. In house integrated L2. Direct white, some remote. Some white plus solutions.

**Will Be** –

- Increasing value seen in Vertical Integration
- L2 products, package free for lower cost
- Building Block approach to mitigate complexity
- Control of distributions and common costs