Recitation 9 - LEDs II: The Revolution - Outline

- **LED practice**
  - Early devices
    - materials
    - device structures
  - Fiber coupled devices
  - Resonant cavity devices
  - Modern devices
    - high efficiency, high intensity advances (getting heat and light out)
    - new material advances (phosphides, nitrides)
    - white light sources

- **Foils from Lumileds**
  - One major player's viewpoint (courtesy Dr. Paul Martin)
Light emitting diodes: fighting total internal reflection

Total internal reflection can be alleviated if the device is packaged in a domed shaped, high index plastic package:

If the device is fabricated with a substrate that is transparent to the emitted radiation, then light can be extracted from the 4 sides and bottom of the device as well as from the top. This increases the extraction efficiency by a factor of 6!
**Light emitting diodes:** fighting total internal reflection

**Transferred substrate technology**

LED heterostructure etched free of its GaAs substrate, and a GaP.

Comparisons of emission and structures of conventional and transferred substrate LEDs.

**Light emitting diodes:** fighting total internal reflection, cont.

Other solutions to the total internal reflection that are not as widely used as these are:

**Thin devices with roughened surfaces:** The idea is that if there is very little internal (re)absorption of the emitted light, the light will bounce around inside the device until it hits the surface at an angle within the critical angle. If the surface is rough, the chance of this happening is increased.

**Resonant cavity LEDs:** If a one-dimensional photonic crystal (a distributed Bragg reflector) is placed on the bottom of the device, the light emitted downward will be redirected up.

**Superluminescent emitting LEDs:** If a device is driven strongly enough, there can be some stimulated emission, and this will be highly directed, as we shall see when we talk about laser diodes. This can be used to increase an LEDs emission.

None of these ideas work as well as using a transparent substrate, collecting the light from all sides of a device, and putting the device in a high-index package positioned in a suitable reflector.
Light emitting diodes: historical perspective

LEDs are a very old device, and were the first commercial compound semiconductor devices in the marketplace. Red, amber, and green LEDs (but not blue) were sold in the 1960's, but the main opto research focus was on laser diodes; little LED research was done for many years.

Then…things changed dramatically in the mid-1990's,
in part because of new materials developed in the search for red and blue lasers, \text{AlInGaP/GaAs, GaInAlN/GaN}
in part because of packaging innovations,
    improved heat sinking and advanced reflector designs
in part due to advances in wafer bonding, and
    transparent substrates for improved light extraction
in part due to the diligence of LED researchers.
    taking advantage of advances in other fields

Why have people cared so much about LEDs?
    a cool, efficient source of light
    rugged with extremely long lifetimes
    can be turned on and off, and modulated, at very high rates
Materials for Red LEDs: GaAsP, AlInGaP, and GaP

Modern AlInGaP red LEDs grown lattice-matched on GaAs, and then transferred to GaP substrates

GaP red LEDs grown GaP and based on Zn-O pair transitions

Early GaAsP red LEDs grown on a linearly graded buffer on GaAs
- Holonyak and Bevacqua, APL 1 (1962) 82.
The III-V wurtzite quarternary: GaInAlN

![Graph showing the energy gap, $E_g$, vs. lattice period, $a$, for AlN, GaN, InN, and the energy wavelength, $\lambda$, vs. lattice period for the quarternary.]  

- **AlN**
  - Good for UV (unique)
- **GaN**
  - Great for blue (the best)
- **InN**
  - Good for green
- **GaInAlN**
  - Not so good for red yet.

C. G. Fonstad, 4/07

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Light emitting diodes - typical spectra

- LED emission - typ. 20 nm wide GaAsP red LED

- Important spectra for comparison with LED spectrum
Light emitting diodes - human eye response
**Light emitting diodes - Red and Amber LEDs**

- Red LEDs
  - \( \lambda = 660 \text{ nm} \)
  - \( \lambda = 690 \text{ nm} \)

- Yellow/Amber LEDs
  - \( \lambda = 620 \text{ nm} \)
  - Orange
  - \( 40 \mu \text{m} \)
  - Yellow
  - \( \lambda = 590 \text{ nm} \)
Light emitting diodes - Conventional green LEDs; Burrus-type

- Green LEDs
- LED designed to couple efficiently to a fiber (Burrus geometry)
Haitz’s Law for LED Flux

- LED Flux per package has doubled every 18-24 months for 30+ Years!!
- 1965 Moore’s Law “# of Transistors/chip will double every 18-24 months!”
Light emitting diodes - illustrating recent advances

• **Above:**
  Larger areas, better heat sinking, and higher drive currents.

• **To the right:**
  TS (transferred substrate) LEDs. Note also the use of heterostructures
Lumileds invests heavily to develop leading technology in LED material. Our AllInGaP technology leads the world in performance for Red, Orange, and Amber light. And we continue to improve performance.
InGaN technology for Green, Blue, and White

HP Indicator LED (1998)

LumiLeds Power LED (1999)

LUXEON (2001)

300x400um²

1000x1000um²

~ 10 x flux improvement

1000x1000um²

~ 17 x flux improvement
High Power LEDs

Luxeon High Power Package Example

- Plastic Lens
- Silicone Encapsulant
- InGaN Semiconductor Flip Chip
- Solder Connection
- Silicon Sub-mount Chip with ESD Protection
- Cathode Lead
- Gold Wire
- Heatsink Slug
High Power LEDs

Die design - flip-chip submount

A silicon submount is utilized for several reasons;
- Silicon & sapphire have similar coefficients of thermal expansion,
- Solder bumping of silicon wafers is an industry standard process,
- A wide range of electronics can be integrated into silicon, enabling a range of advanced products,
- A hexagonal shape provides a compact optical element.
- Extraction efficiency 2x higher than conventional GaN LEDs
- Power per LED ~1-2 orders of magnitude higher.
Illumination Markets

How Much Energy is Used for Lighting

- In 1999 the US used 3 Trillion kWhr of Electricity!

- 20% or 600 Billion kWhr of Electricity generated was used in Lighting!

- Incandescent/Hal. lamps burn 40% of electricity to produce 15% of light!

- Fluorescent/HID lamps use 60% of electricity to produce 85% of light!

- Illumination market is $60Billion/yr and growing slowly, ~2%/yr

- Worldwide, similar 20% of energy on lighting.
Common Low Wattage Bulbs

White LED technologies share **Four** challenges!

- Maximize efficiency - lm/W
- Color Control: CCT, Ra
- Maximize flux density - lm/package
- Increase the Flux per Buck - kLm/$

<table>
<thead>
<tr>
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<th>15 W</th>
<th>4 W</th>
<th>20 W</th>
<th>45 W</th>
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<tr>
<td>Power</td>
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<td>145 lm/bulb</td>
<td>320 lm/bulb</td>
<td>475 lm/bulb</td>
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<tr>
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<td>7 lm/W</td>
<td>36 lm/W</td>
<td>17 lm/W</td>
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<td>Incandescent</td>
<td>Fluorescent</td>
<td>Halogen</td>
<td>Incandescent</td>
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</table>
Illumination Markets

Incandescent Bulbs

- Incandescent = hot light, emitted from a (tungsten) filament at around 2800°K
  - Disadvantages:
    - mostly infra-red
    - glass vacuum envelope & filament both break easily
    - <15 lm/W luminous (<5% power) efficiency
    - fire hazard, burnt fingers, maintenance
  - Advantages:
    - Radiant cooling
    - Cheap 0.0005$/lumen
    - klm per package!

Basic disadvantage:
Lots of heat AND
no chance to come close
to DAYLIGHT = 6500°K

Courtesy Gerd Mueller LL
Illumination Markets

Fluorescent Bulbs

- Fluorescent = cold light, emitted by phosphors excited by gas discharge.
  - Advantages:
    - High efficiency 80+lm/W & High Flux klm/lamp
    - Moderate cost for large lamps 0.002$/lm
  - Disadvantages:
    - Lifetime short <10,000 hrs resulting in high maintenance.
    - Glass vacuum envelope leaks/breaks, ballast noisy.
    - Mercury!!

Basic Advantage:
any color temperature possible by tri-color mixing

Courtesy Gerd Mueller LL
White Light from LEDs

Three methods of Generating LED White Light

• Each method has potential strengths!

Red + Green + Blue LEDs

UV LED + RGB Phosphor

Binary Complimentary

RGB LEDs

UV LED + RGB phosphor

Blue LED + Yellow phosphor

Copyright (c) Lumileds Lighting LLC Company
White Light from LEDs

White from Blue LED + Phosphor(s)

- **Advantages:**
  - Simple and single Yellow phosphor versions available today!
  - Decent color rendering (Ra = 75 for Blue LED + Yellow Phosphor)

- **Disadvantages**
  - Limits on efficiency due to Stokes shift, self absorption, temperature effects…
  - Better color rendering (i.e. multi phosphor comes at cost of luminous efficiency!)

- **So how does this approach measure up using our OIDA metrics? (YAG + blue)**
  - Knowns: $\varepsilon_{o,ph} [\text{lm/W}_o] \sim 330 \text{lm/W}_o$, $\eta_{QD} = 80\%$, $\eta_{ph(25C)} > 95\%$

\[
\varepsilon_{e,white} [\text{lm/W}_e] = \text{WPE}(T) \times \varepsilon_{o,ph} [\text{lm/W}_o] \times \eta_{QD} \times \eta_{ph(T)} \times \eta_{pkg}
\]

- For 150lm/W $\text{WPE}(T, I) \times \eta_{pkg} = 60\%$ at appropriate temperature & drive!
- For 200lm/W $\text{WPE}(T, I) \times \eta_{pkg} = 80\%$ at appropriate temperature & drive!
- Today’s production best is from Lumileds at $\sim 10\%$ :-)
Today, PC LEDs are in the 20-30lm/W range!

- Todays white LEDs are in the ~20-30lm/W range!

Ce$^{3+}$ doped garnet family, e.g. (Y,Gd)$_3$Al$_5$O$_{12}$

Combined with the same LED, Ce$^{3+}$ phosphors hit the Planckian at different color temperatures:

Ra = 75 is not great (good FL has 83) but it is OK for some applications.
Adding green and red to the blue of the LED opens a huge color gamut and allows for *de-luxe* white of any color temperature – one option:
- \( \text{SrGa}_2\text{S}_4:\text{Eu}^{2+} \) - green
- \( \text{SrS}:\text{Eu}^{2+} \) - red

The dipole-allowed 5d-4f transitions of \( \text{Ce}^{3+} \) and \( \text{Eu}^{2+} \) are uniquely suited for color converters:
- high absorption, small
- Stoke’s shift
White Light from LEDs

White from UV LED + RGB Phosphors

- **Advantages:**
  - White point determined by phosphors ONLY! (i.e. tolerant to LED variation)
  - Excellent color rendering possible!
  - Superficially “Simple to manufacture!” Reality is not so simple!
  - Temperature stability of phosphors. (Can be great!)

- **Disadvantages**
  - Potential for damaging UV light leakage.
  - Limits on efficiency due to Stokes shift, self absorption, temperature effects,…

- **So how does this approach measure up using our OIDA metrics? (UV + RGB)**
  - Knowns: \( \varepsilon_{\text{O,ph}} \frac{\text{lm}}{\text{W}} < 300 \frac{\text{lm}}{\text{W}}, \quad \eta_{\text{QD}} = 70\% (380\text{nm}), \quad \eta_{\text{ph}(25\text{C})} > 95\% \) (guess?)

\[
\varepsilon_{\text{e,white}} \left[ \frac{\text{lm}}{\text{W}_{\text{e}}} \right] = \text{WPE}(T) \times \varepsilon_{\text{O,ph}} \left[ \frac{\text{lm}}{\text{W}_{\text{o}}} \right] \times \eta_{\text{QD}} \times \eta_{\text{ph}(T)} \times \eta_{\text{pkg}}
\]

- For 150lm/W \( \text{WPE}(T, I) \times \eta_{\text{pkg}} = 75\% \) at appropriate temperature & drive!
- For 200lm/W \( \text{WPE}(T, I) \times \eta_{\text{pkg}} = 100\% \) at appropriate temperature & drive!
UV LED pumped RGB Phosphors

**UV LED must be >2x Green LED WPE for same lm/W!**

- Downshift in color causes fundamental energy loss.
- Scattering in phosphor + absorption in package (incl. phosphor) reduces extraction efficiency! Today’s best package efficiency is ~50% for Blue + Yellow phosphor, UV + RGB phosphor likely to be even worse!

![Graph showing power conversion vs. UV pump wavelength](image)

Assuming 50% pkg. Efficiency!
White Light from LEDs

**White from RGB LEDs**

- **Advantages:**
  - Long term likely the most efficient!
  - Excellent color rendering possible! (There is a price thou
  - Very large color Gamut available!
  - Dynamic tuning & monitoring of color point possible!

- **Disadvantages**
  - Temperature stability of LEDs varies with color.
  - Dynamic tuning & monitoring of color point required?!

- **So how does this approach measure up using our OIDA metrics? (UV + RGB)**
  - Knowns: $\eta_{O,RGB} \ [\text{lm/W}] \sim 300\text{lm/W}$, $\eta_{OD} = 100\%$, $\eta_{ph(25C)} = 100\%$

\[
\text{WPE}(T) \cdot \text{WPE}(T, I) = \frac{\text{lm}}{\text{W}}
\]

- $\varepsilon_{\text{e,white}} [\text{lm/W}] = \text{WPE}(T) \cdot \varepsilon_{\text{o,ph}} [\text{lm/W}] \cdot \eta_{OD} \cdot \eta_{ph(T)} \cdot \eta_{pkg}$

- For 150lm/W $\text{WPE}(T, I) \cdot \eta_{pkg} = 50\%$ at appropriate temperature & drive!
- For 200lm/W $\text{WPE}(T, I) \cdot \eta_{pkg} = 67\%$ at appropriate temperature & drive!
High Power White LEDs

And the efficiency winner is?

- **UV + RGB phosphors IF**
  - UV LED is fundamentally ~2x higher WPE than green LED?
  - And RGB phosphors with high efficiency at high temperature can be found?

- **Blue + Yellow phosphor IF**
  - Blue LED is fundamentally ~1.5x higher WPE than green LED?
  - And phosphor with Ra > 85 & high efficiency at high T can be found?

- **Red, Green and Blue LED IF**
  - AlInGaP T0 can be raised or other Red semiconductor can be mastered?
  - Will InN ever make efficient Red?

Everyone place your bets!
Conclusion!

Fast forward: 25 years

What’s a lightbulb and why would anyone want to change one?
Red LEDs for Green Groceries

Growing hydroponic lettuce under red LEDs, the color used by chlorophyll, a factory east of Tokyo produces 7000 heads of lettuce/day in a ten story building with a 1000 m² footprint. The heads mature 3 times faster than outdoors, and the electric bill is 60% less than with fluorescent lighting.

It is still cheaper to grow lettuce outdoors, but there are no weather problems or bugs.

High Power White LEDs

5mm Indicator Package Example

LED Chip Conductive Epoxy Die Attach; Ball Wire Bond Onto Top Contact

Wedge Wire Bond

Lens (Diffuser)

Cathode (-) Anode (+)