Light Emitting Diodes

Outline

- Luminescence Spectra of Atoms

- LEDs
  . p-n Junction
  . Light Outcoupling

- Organic LEDs
- Quantum Dots in LEDs
**Characterization of Organic Illumination Systems**

April 1, 1989, Hamburgen *et al.*

<table>
<thead>
<tr>
<th>Subject</th>
<th>Electrode Orientation</th>
<th>Electrode Separation</th>
<th>Electrode #1 Penetration</th>
<th>Electrode #2 Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bok Choy</td>
<td>parallel</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Mandarin Orange</td>
<td>parallel</td>
<td>0.38</td>
<td>0.38</td>
<td>0.38</td>
</tr>
<tr>
<td>Cornichon</td>
<td>axial</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Kosher Pickle</td>
<td>axial</td>
<td>2.5</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Dill Pickle</td>
<td>axial</td>
<td>2.5</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

**Electrode Position:**

- Thermocouple Probe
- Device Under Test

- Electrode #1 Penetration
- Electrode Separation
- Electrode #2 Penetration
High energy electrons (n-type) fall into low energy holes (p-type)
p-n Junctions and LEDs

Small Gap

Red Light Emitted

Large Gap

Yellow Light Emitted

ENERGY
Homojunction p-n Light Emitting Diode

ELECTRICITY IN → LIGHT OUT

Forward Bias condition

Zero bias condition

\[ I = I_S \left( e^{\frac{qV_D}{kT}} - 1 \right) \]

Diode Current

Saturation Current in Reverse Bias

Boltzmann Constant

Temperature

Breakdown Voltage \( V_B \)

Forward Current

Leakage Current

Avalanche Current

Reverse Voltage

Voltage Across Diode
Extraction Efficiency of Planar LEDs

- Critical angle of total internal reflection
- Problem: Only small fraction of light can escape from semiconductor.

\[
\frac{P_{\text{escape}}}{P_{\text{source}}} \approx \frac{1}{2} \left[ 1 - \left( 1 - \frac{\phi_c^2}{2} \right) \right] = \frac{1}{4} \phi_c^2
\]

\[
\phi_c = \sin^{-1} \left( \frac{n_2}{n_1} \right)
\]

- \( \phi_c \) = critical angle of total internal reflection
- Problem: Only small fraction of light can escape from semiconductor.

\[
\frac{P_{\text{escape}}}{P_{\text{source}}} = 1 \frac{n_{\text{air}}}{4 \ n_s^2}
\]

- Above equation gives < 10% extraction efficiency for typical III-V.
Artificial Lighting consumes 8% of US energy and 22% of US electricity. The energy cost is estimated at $50B annually or $200 per capita.
<table>
<thead>
<tr>
<th>INSTALLED</th>
<th>EFFICIENCY</th>
<th>FRACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent</td>
<td>5%</td>
<td>12%</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>20%</td>
<td>62%</td>
</tr>
<tr>
<td>HID lamps</td>
<td>25%</td>
<td>26%</td>
</tr>
<tr>
<td>White LEDs</td>
<td>35%</td>
<td>----</td>
</tr>
</tbody>
</table>

Note: Electric Motor Efficiency is 85%~90%
Survey of Lightbulb Technology Performance
(using data from bulbs.com)

Luminescence Efficiency [lm/W]

Color Rendering Index

QD VISION
NEXXUS 110V LED
COMPACT FLUORESCENT
CREE LR6 LED
CREE LRP38 LED
OTHER LED TECHNOLOGIES
HALOGEN
INCANDESCENT
OLED: The Green Display

TV and PC Account for 1% each of US Electricity Usage

Plasma, LCD, RPTV power usage values from 2007 CNet report on commercial TV power consumption. OLED value projected from SID 2007 demo. US household power usage data from 2004 report by the Natural Resources Defense Council.