RGB+ lighting

... is the path to 250 lm/W warm white

which means ...

SSL can broadly challenge tube fluorescents in commercial lighting and lower the cost of incandescent replacements (less heat to dissipate)

with ...

additional functionality of color tunability
**Efficiency of RGB+**

<table>
<thead>
<tr>
<th>CCT (K)</th>
<th>Maximum LER (lm/W)</th>
<th>Efficacy for 67% Conversion (lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CRI 70</td>
<td>CRI 85</td>
</tr>
<tr>
<td>5000</td>
<td>380</td>
<td>365</td>
</tr>
<tr>
<td>3800</td>
<td>407</td>
<td>389</td>
</tr>
<tr>
<td>2700</td>
<td>428</td>
<td>407</td>
</tr>
</tbody>
</table>

- When RGB all exceed 40% wall plug efficiency, then 150 lm/W color-tunable white is achievable.
- Red and blue are already at this performance.
- Improving green is the key.
Science Challenge : Green Efficiency

High-power (≥ 1 Watt input) visible-spectrum LEDs

Fig. 2. State-of-art external quantum efficiencies for high-power visible-spectrum LEDs ($T_j = 25^\circ C$): (1) InGaN VFFC LEDs, 350 mA (this paper); (2) InGaN VTF LED, 1000 mA [42]; (3) InGaN CC LEDs employing patterned substrates [35]; and (4) Production performance, AlGaInP TIP LEDS [9], Philips Lumileds Lighting Co., 350 mA. $V(\lambda)$ is the luminous eye response curve from CIE. Dashed lines are guides to the eye.


Green gap

~20% WPE

Start by doubling...
Semiconductors emitting in the green

Today’s contenders: AlInGaP, w-InGaN – dominant LED materials
Can others play? ZnCdSe? Cubic InGaN? long list...

"Italics" = indirect gap
"Roman" = direct gap
diamond = hexagonal structure
square = cubic structure

Fig. 21.4. Room-temperature bandgap energy versus lattice constant of common elemental and binary compound semiconductors.
AlInGaP – a fundamental energy band problem with green

Almost 100% efficiency can be achieved here

Only a few% efficiency here

Almost 100% efficiency can be achieved here
InGaN bandstructure – looks good


Indirect band minima located far from Γ point
Auger recombination contributes

- Green c-plane QWs exhibit more Auger recombination than Blue QWs because QCSE reduces rate coefficients

Non-polar planar could help, but growth conditions and strain hurt...

- More indium is needed when growing on non-polar plane → need to lower growth temperature → more non-radiative recombination centers


Too thin! Can’t make a QW

InGaN alloy tries to relieve its stress by becoming nonuniform, even in the blue compositional range

Near-field PL

- Effect is stronger in the green
- Limiting factor for green laser performance
- Optimization of growth conditions by several groups trying to address this

Tilt domains observed in XRD


Growth on “foreign” substrates which relieve strain

- InGaN lattice matched to ZnO

Other approaches:
- strain-relaxed InGaN-on-sapphire templates from Soitec (epitaxial lift-off)
- other ways?

Drawbacks: substrate cost has to be competitive with sapphire
Nanometer texturing/nanowires to address these issues

- Glo nanowire LEDs

- Provide textured template for InGaN to “master” the strain
- Small sizes → edges, corners can accommodate stress, enabling a defect-free QW
- Can be cost effective, uses many existing materials & technologies
Better green is a tough problem....

worth solving ...

for SSL and many other applications (displays, medical instrumentation)

High risk & high reward ---- Core Technology