The Green Gap:

Challenges in Achieving High Efficiency Green LEDs for Solid State Lighting

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Outline

• Motivation
• Principles of operation
• Approaches
  – III-P
  – III-N
  – II-VI
• Improving external quantum efficiency
• Conclusions
Lighting Trends
Lighting Trends

• 22% of all the electricity generated in the US spent on lighting
  – 0.03% solid state lighting
Funding/Market

- Market for high brightness LEDs: $5.1 billion
  - For solid state lighting: $450 million

DOE Multi-Year Program Plan FY’09-FY’15: Solid-State Lighting Research and Development
Creating White Light

• Blue/UV LED + phosphor
  – 263 lm/W (blue LED)
  – 203 lm/W (UV LED)
  – Stokes shift: inherent loss in phosphor down-conversion

• Color mixing
  – 408 lm/W (RGYB)

• Limitation: No High Brightness GREEN LEDs!!!
Device Operation

Materials Choices

- AlInGaP
- InGaN
- ZnSe
The Green Gap

AlGaInP

**AlGaInP: direct-indirect transition**

Direct-indirect gap transition  
556-532 nm

Compressive strain increases bandgap of InGaP


AlGaInP: electron blocking

Tensile strain increases bandgap of AlInP


InGaN

InGaN: substrate

- SiC, sapphire
  - high lattice mismatch.
  - threading dislocations $10^7$-$10^8$ cm$^{-2}$

- Solutions:
  - ELOG
  - GaN substrate
InGaN: Polarization

InGaN: In challenges

• In composition increases, growth temperatures decrease
  – Greater concentration of point defects

• Composition inhomogeneities
  – Conventionally thought to be beneficial
  – Effect of non-uniform strain and polarization requires further investigation
ZnSe

ZnSe system: Challenges

- device lifetime
  - defect density
    - polar
    - low growth temperatures
  - large tensile strain in ZnS$_{0.07}$Se$_{0.93}$
    - large thermal expansion mismatch with GaAs
  - defects mobile, weak bonding
    - Dislocation accumulation in active region at modest current densities
ZnSe: Solutions

- Native ZnSe substrates
  - lifetime of 675h (15 A/cm$^2$)
  - transparent substrate

- Add Be
  - decrease the mobility of the dislocations that do exist
  - BeSe and BeTe more covalent, lower dislocation velocity

- Incorporate better electron-blocking layers
  - Prevent electron overflow into the p-cladding layers
  - lifetime 10,000h (14.3 A/cm$^2$)

Improving extraction efficiency

• “borrow” techniques from other high brightness LEDs/laser diodes
  – transparent substrates
  – Bragg reflectors
  – resonant cavities
  – photonic crystals
  – surface texturing
  – encapsulation in hemispherical packaging
Conclusions

• **The common trend**
  – Reduce dislocations/defects to reduce non-radiative recombination sites and increase lifetime

• **AlGaInP**
  – Quaternary system, most difficult to control
  – Indirect gap transition a problem
  – Most established technology, compatible with red

• **InGaN**
  – New technology, more understanding required
  – Great potential, compatible with blue

• **ZnSe**
  – Lifetime is major problem

• **COST is important!!!**