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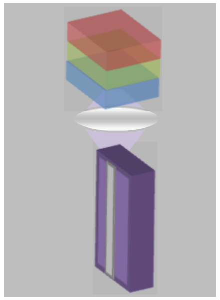

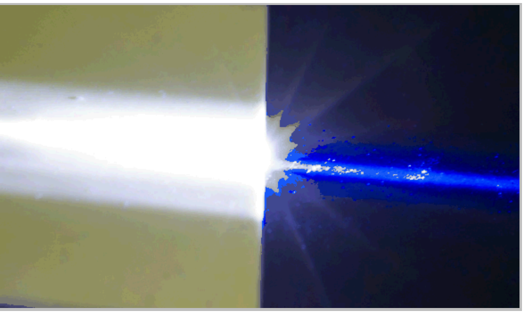

Laser Diodes for Solid-State Lighting

Jonathan J. Wierer, Jr. * **and Jeffrey Y. Tsao**

**jwierer@sandia.gov*

SPIE Optics+Photonics, San Diego, CA 20 Aug 2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

SSLS EFRC

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Outline

- Efficiency comparison and projections for blue LEDs and laser diodes (LDs).
- White light from LDs.
- LD System benefits.
- Economic comparison for LEDs and LDs.

Efficiency comparison and projections of LEDs and LDs

III-nitride blue LEDs vs. LDs

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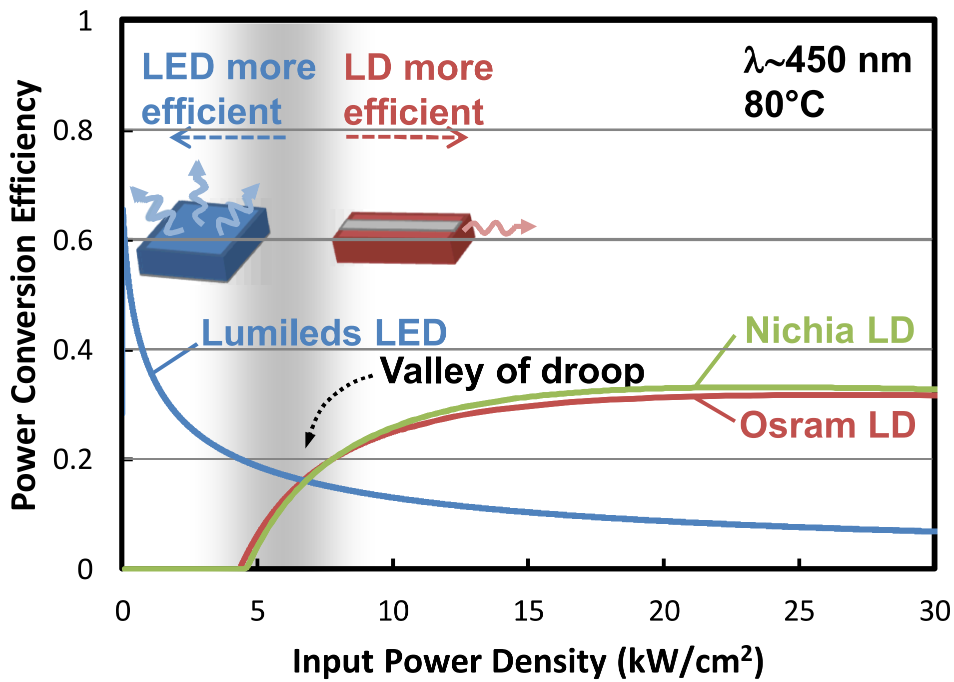
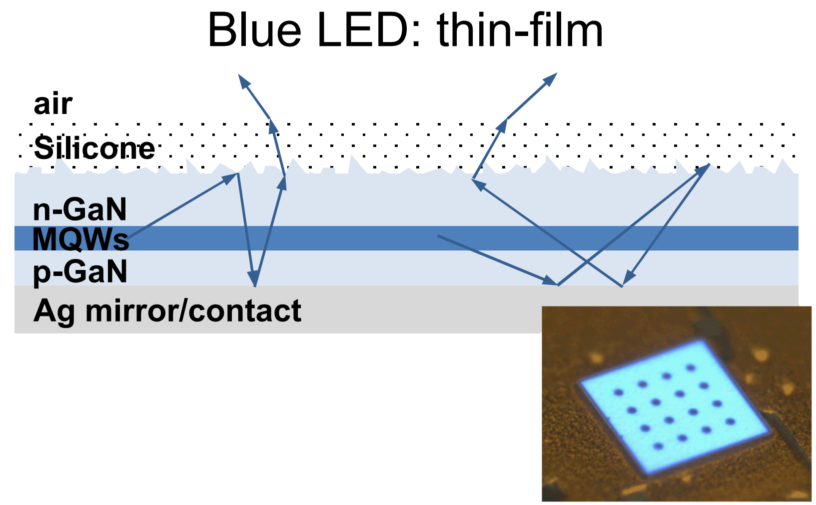
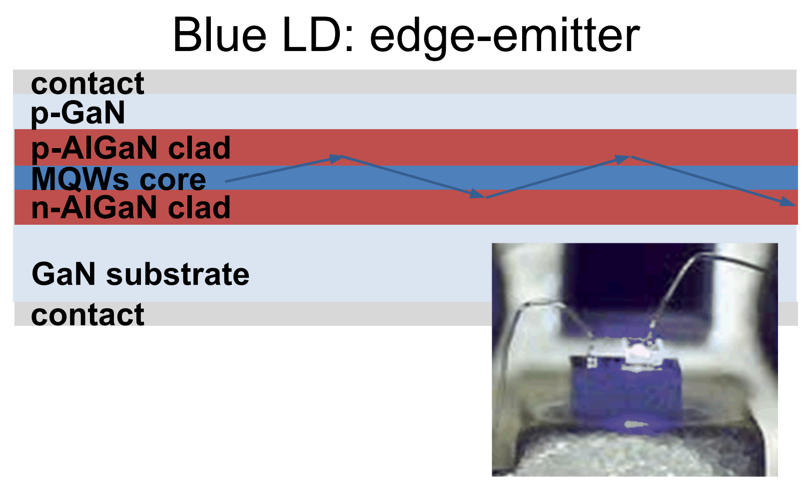


J. J. Wierer, Jr., D. S. Sizov, and J. Y. Tsao, *“Comparison between Blue Laser and Light-Emitting Diodes for Future Solid-State Lighting*”, Laser and Photonics Review (2013).

- After threshold LDs are not affected by efficiency droop.
- LDs are more efficient at higher input power densities.





State-of-the-art blue LED

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- Joule Efficiency: η_J
  - $\eta_J = h\nu/qV$
  - $V = V_D + IR_s.$
  - $V_D = n_f \frac{kT}{q} ln\left(\frac{I}{I_o}\right)$

R_s	0.26 (ohms)
I_o	9×10^{-26} (A)
n_f	1.62

- Injection efficiency: η_{inj}
  - Function of the bandstruture, carrier lifetimes, and internal and external fields.

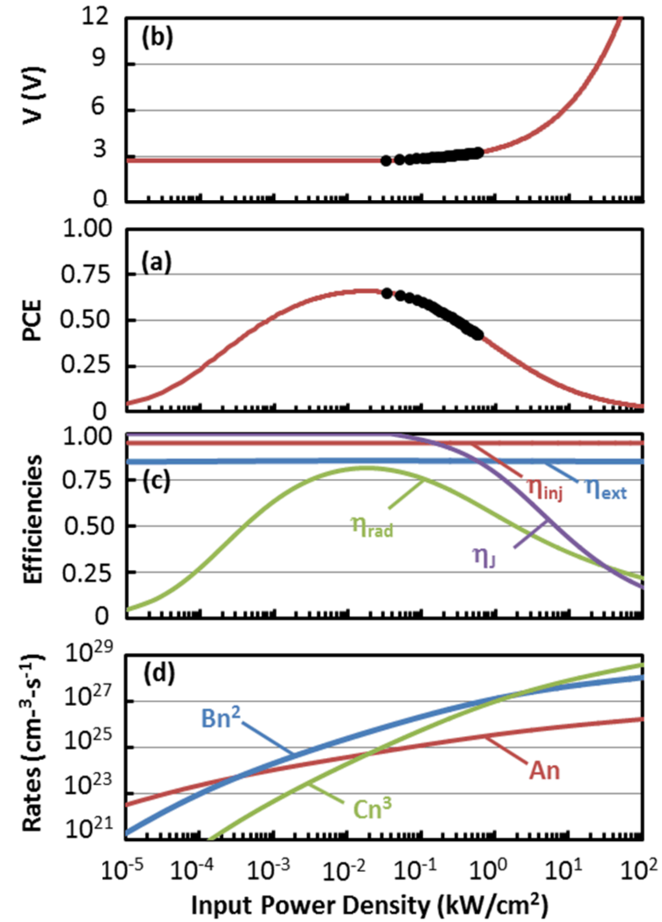
η_{inj}	0.97

- Radiative efficiency: η_r
  - $\eta_r = \frac{Bn^2}{An+Bn^2+Cn^3}$
  - $B = B_0/\left(1+\frac{n}{n^*}\right)$
  - $\frac{n_{inj}I}{qdA_{LED}} = An + Bn^2 + Cn^3$

A	2×10^6 (1/s)
B_o	7.88×10^{-12} (cm^3/s)
C_o	3.15×10^{-31} (cm^6/s)
n*	2.2×10^{19} (1/cm^3)
d	3 x 2.5 nm

- Extraction efficiency: η_{ext}
  - $\eta_{ext} \cong \sum_{b=1}^{\infty}\frac{1}{2}(1-T)^{b-1}T[R_m^{b-1}+R_m^b]$

η_{ext}	0.81
T	0.27
R_m	0.93



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Projection of LED improvements

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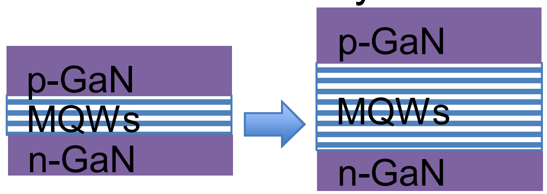
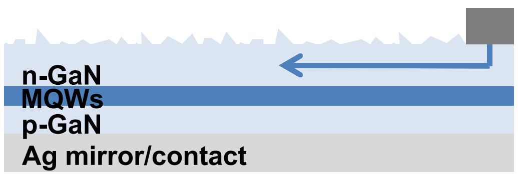
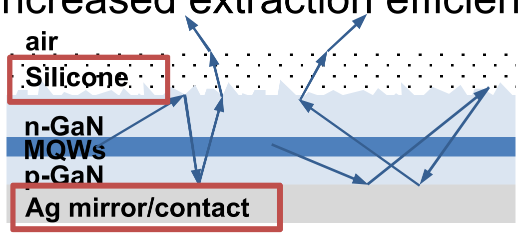
- Increased active layer thickness:



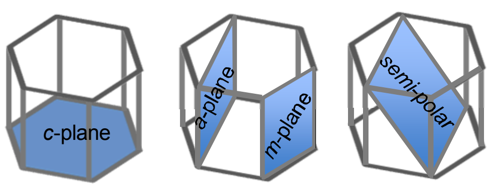
- Reduced series resistance:

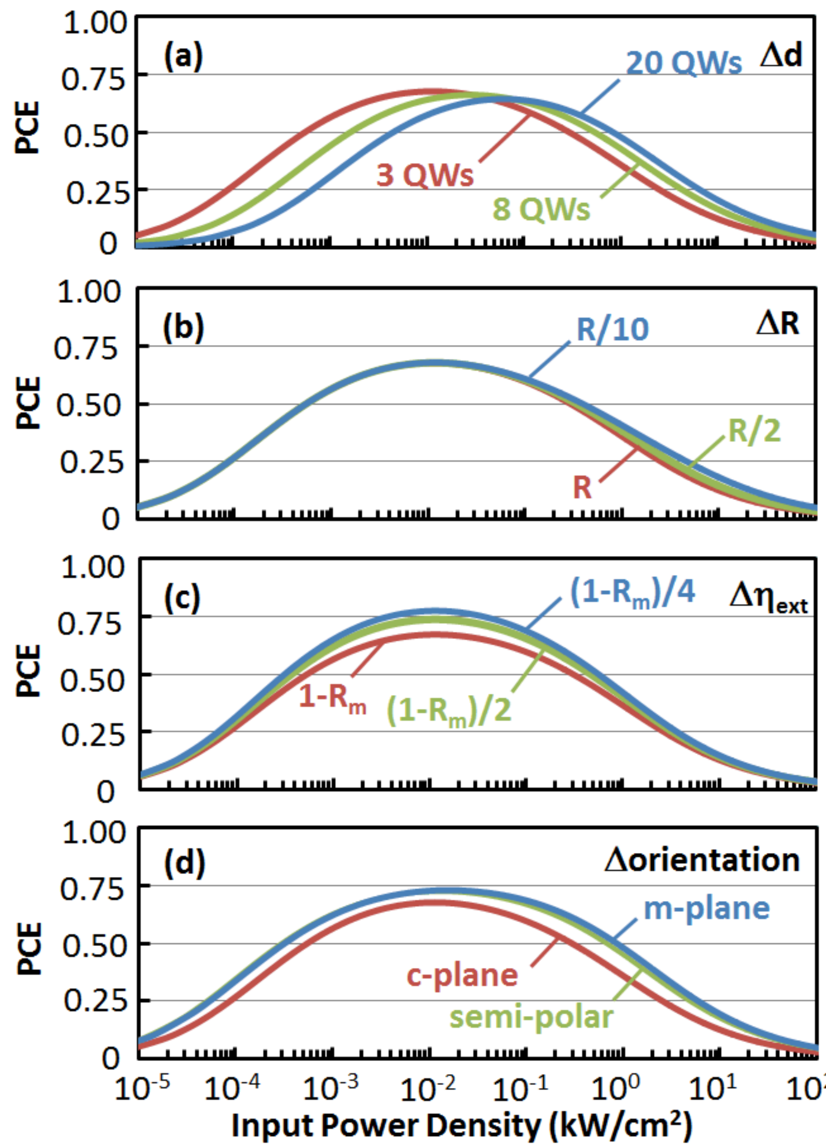


- Increased extraction efficiency:



- Change crystal orientations:





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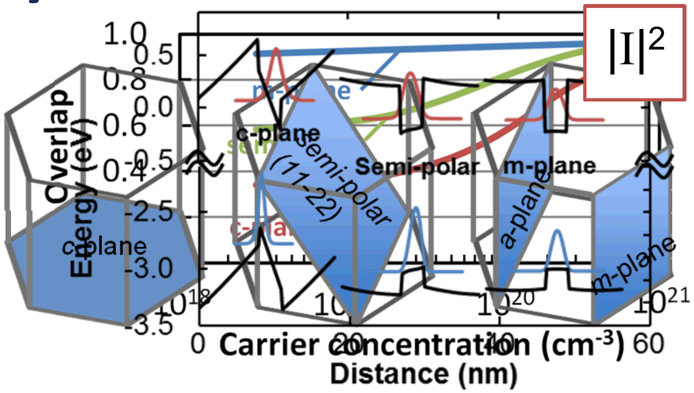
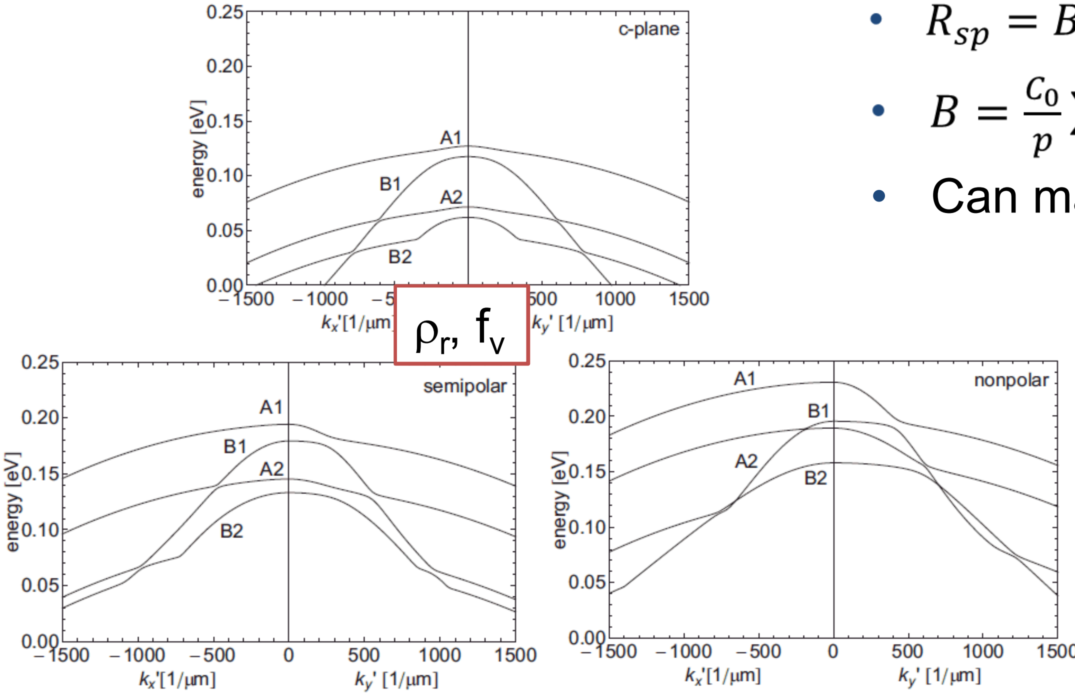
Crystal orientation

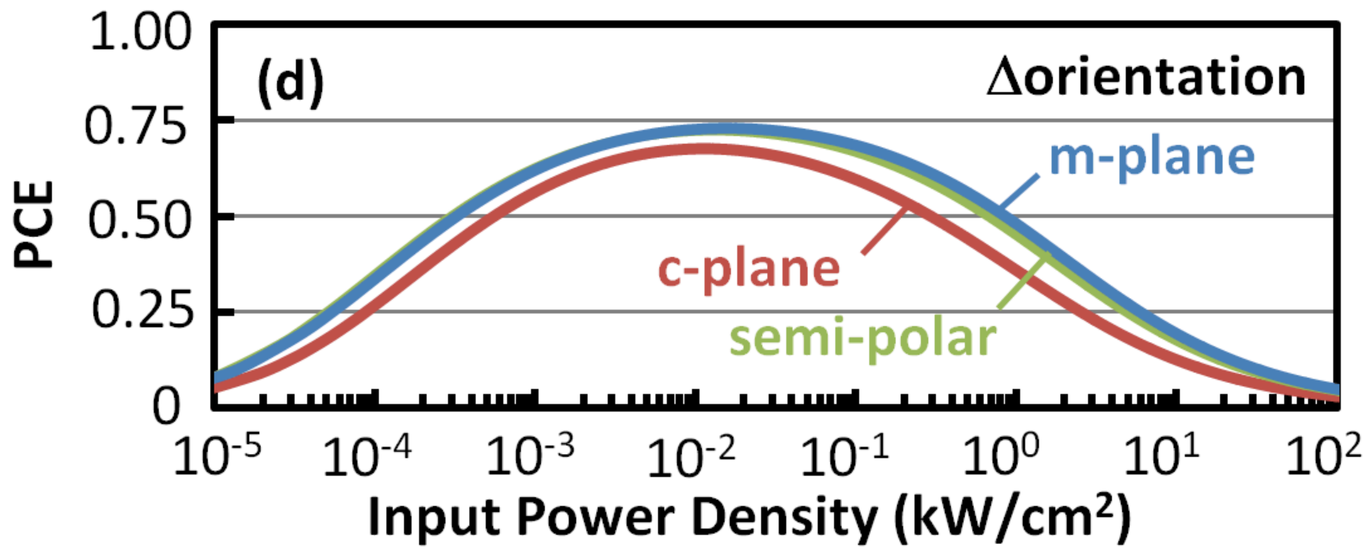




- $\eta_r = \frac{Bn^2}{An+Bn^2+Cn^3}$
- $R_{sp} = Bnp = \frac{\pi q^2}{n_{opt} c \varepsilon_0 m_0 \omega} \sum |I|^2 |\hat{e} \cdot p|^2 \rho_r f_c f_v$
- $B = \frac{C_0}{p} \sum_{i=A1,B1} |\mathrm{I}|^2 \rho_{r,i} f_{v,i}$
- Can make similar arguments for A and C.

W. G. Scheibenzuber et al. PRB, 90, 115320 (2009).

Crystal orientation



- Efficiency curve is "wider".
- The increase in A and C limit the peak efficiency improvement.
- Efficiency droop is not fixed but improved.
    - At 1kW/cm^2 PCE ~ 38% c-plane

      PCE ~ 48% for m-plane

State-of-the-art blue LD

- Joule Efficiency: η_J
  - $\eta_J = h\nu/qV$
  - $V = V_D + IR_s.$
  - $V_D = n_f \frac{kT}{q} ln\left(\frac{I}{I_o}\right)$

R_s	1.02 (ohms)
I_o	6.5×10^{-24} (A)
n_f	2

- Injection efficiency: η_{inj}
  - Function of the bandstruture, carrier lifetimes, and internal and external fields.

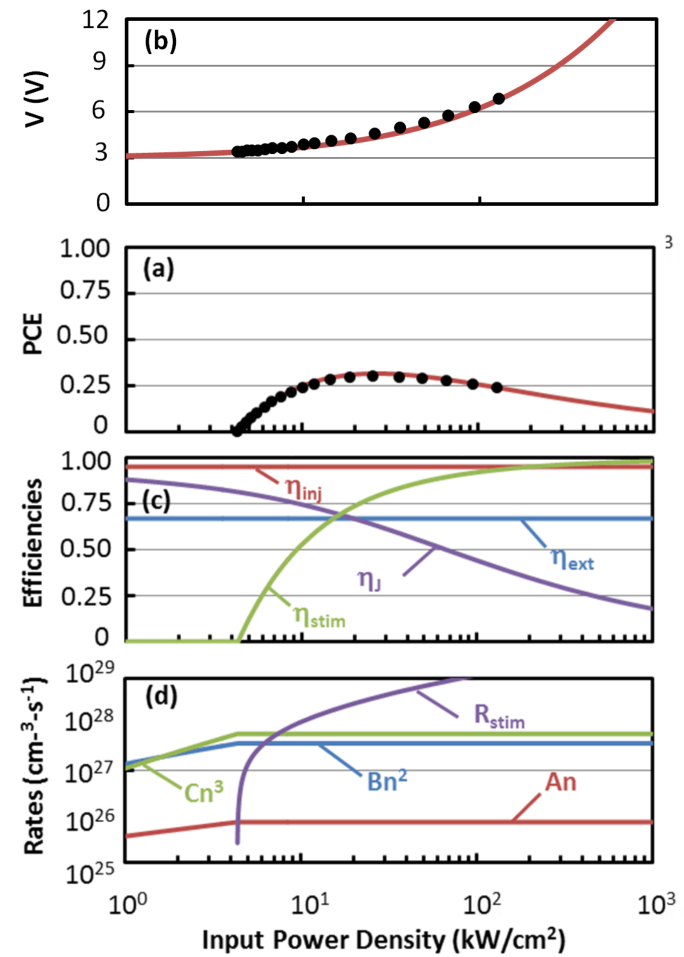
η_{inj}	0.97

- Stimulated efficiency: η_{stim}
  - $\eta_{stim} = (I - I_{th})/I$
  - $I_{th} = \left(\frac{qdA_{LD}}{\eta_{inj}}\right)\left[\left(Bn_{tr}^2 \exp\left(2\frac{\alpha_m+\alpha_i}{\Gamma g_0}\right)\right) + \left(Cn_{tr}^3 \exp\left(3\frac{\alpha_m+\alpha_i}{\Gamma g_0}\right)\right)\right]$

A,B$_o$,C$_o$ n*,d	Same as LED
α_i	6 (1/cm)
α_m	12.1 (1/cm)
n_{tr}	1.75×10^{19} cm^{-3}
Γg_0	23.9 (1/cm)
A_{LD}	1.8×10^{-4} (cm^2)

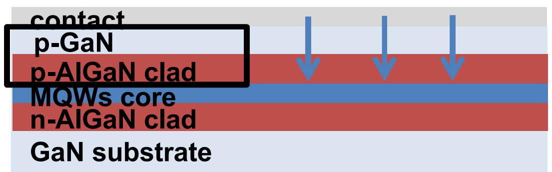
- Extraction efficiency: η_{ext}
  - $\eta_{ext} = \alpha_m/(\alpha_m + \alpha_i)$
  - Shared with η_{stim}

α_i	6 (1/cm)
α_m	12.1 (1/cm)

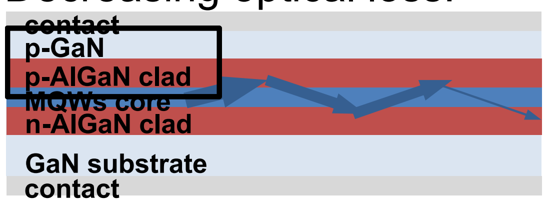


Projection of LD improvements

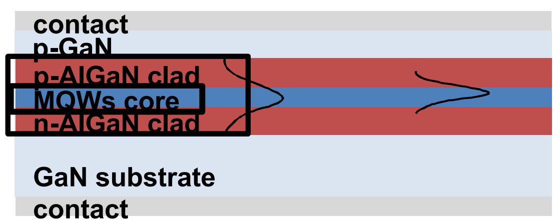
Reduced series resistance:



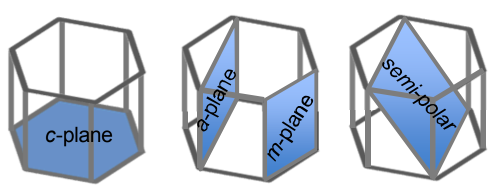
Decreasing optical loss:

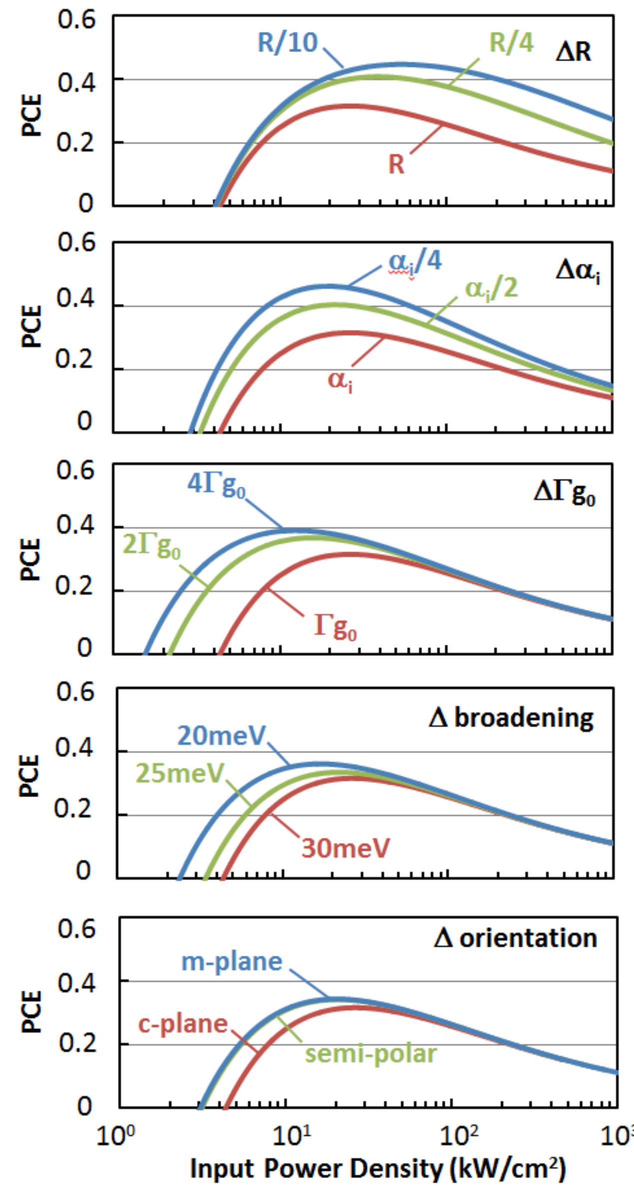


Increasing modal gain:

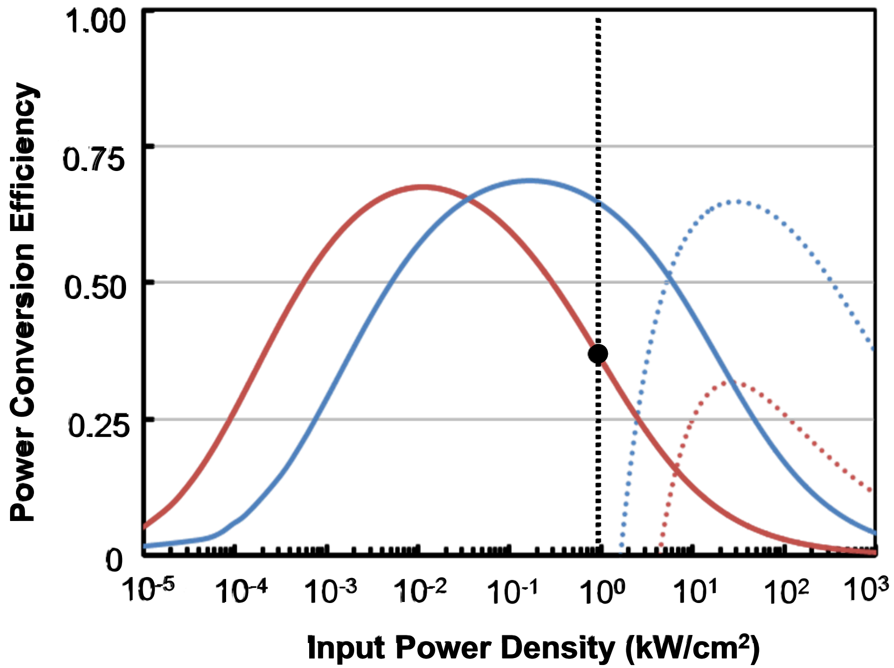


Change crystal orientations:





Projection of efficiency improvements



LED

	Now	Future
# MQWs	3	20
Rs	0.25Ω	0.025Ω
next	83%	96%
orientation	c-plane	m-plane

LD

	Now	Future
Rs	1ohm	0.1ohm
Internal loss	6/cm	1.5/cm
modal gain	23.5	94
broadening	30meV	20meV
orientation	c-plane	m-plane

- Blue LD has the potential to have similar peak efficiencies as LEDs, but at much higher output powers.

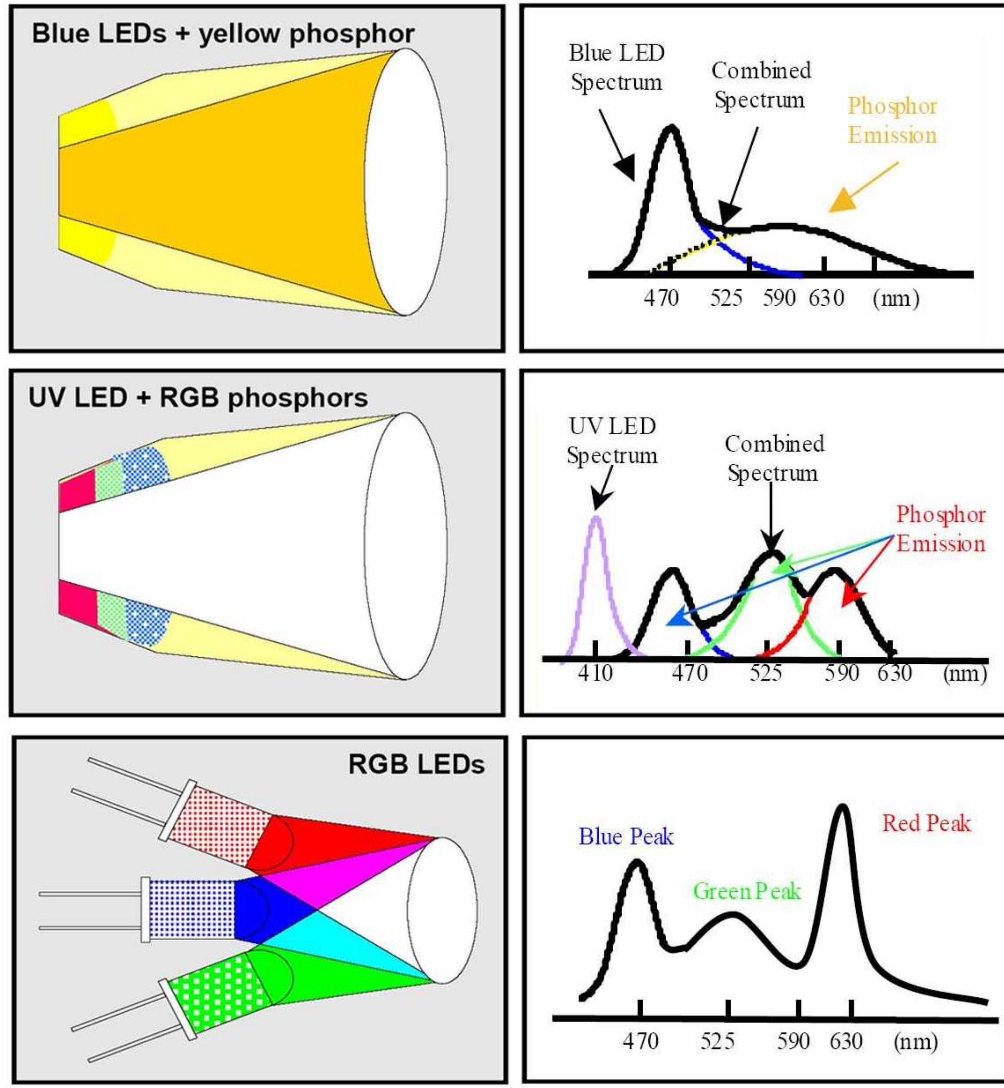
White light from LDs

White LEDs

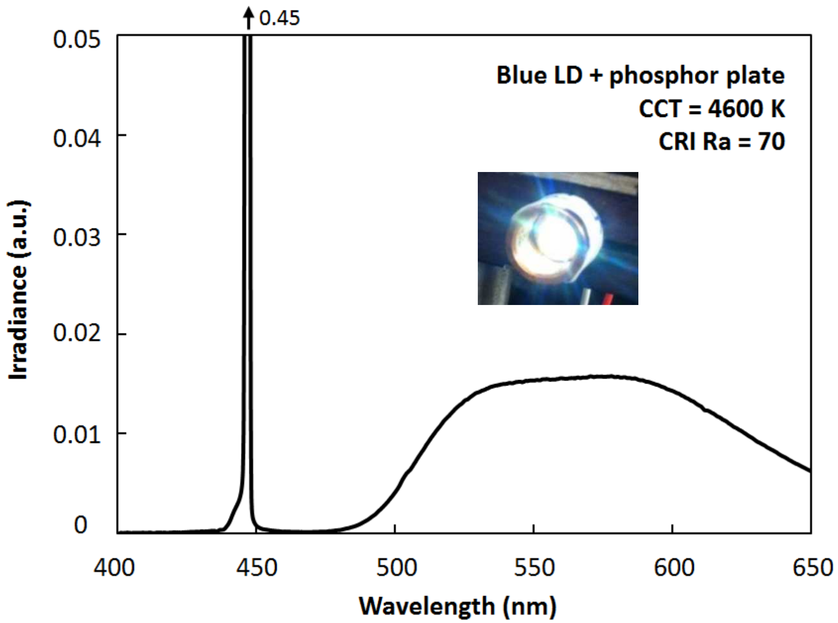
- Blue LED + yellow phosphor
  - Simple
  - Decent color rendering (R_a ~ 75)
  - Stokes-shift loss - blue → yellow

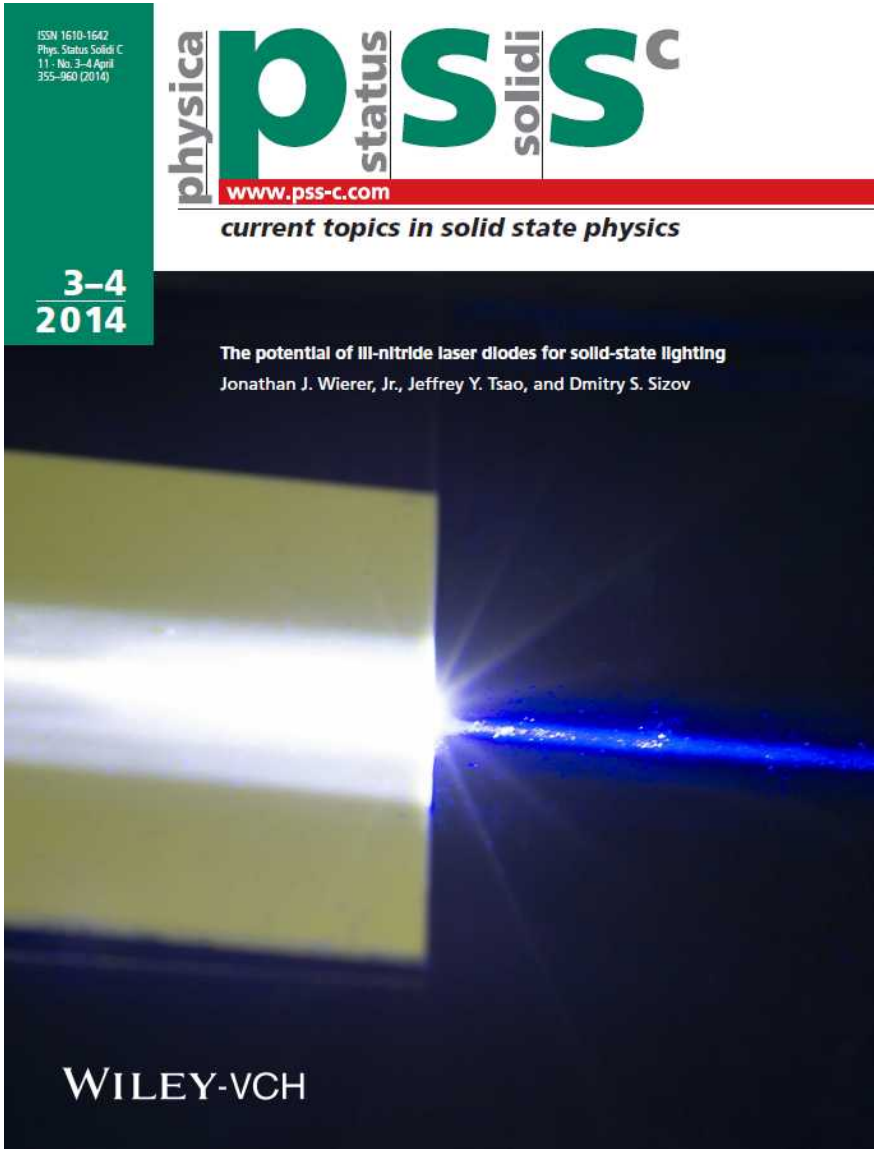
- UV LED + RGB phosphors
  - White determined by phosphors
  - Excellent color rendering
  - Stokes-shift UV → visible colors

- Direct – RGB LEDs
  - Potentially highest efficacy
  - Very large color range
  - Most efficient – tunable white



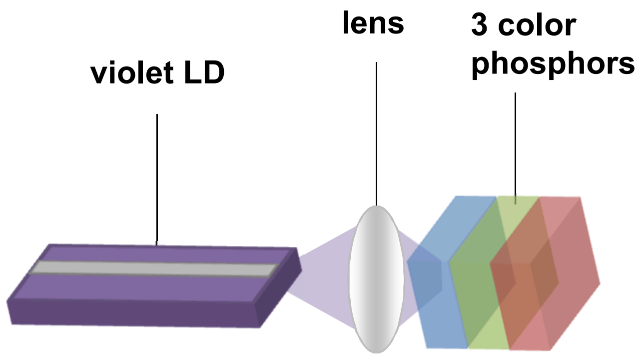
Phosphor converted LD (PC-LD) white

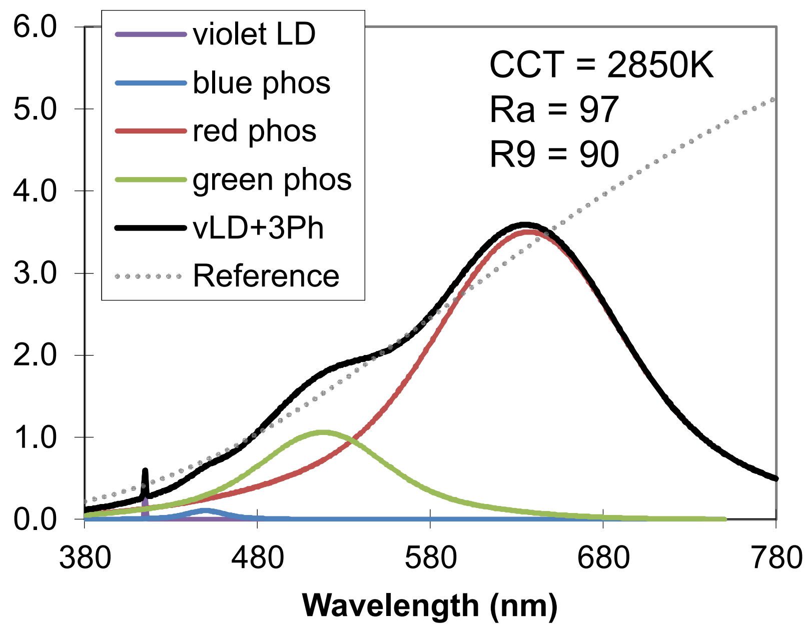




- Commercial blue LD + ceramic phosphor.
- Color temperature and rendering are comparable to PC-LED.
- Blue LDs can be used to produce white light.

Violet pumped PC-LD

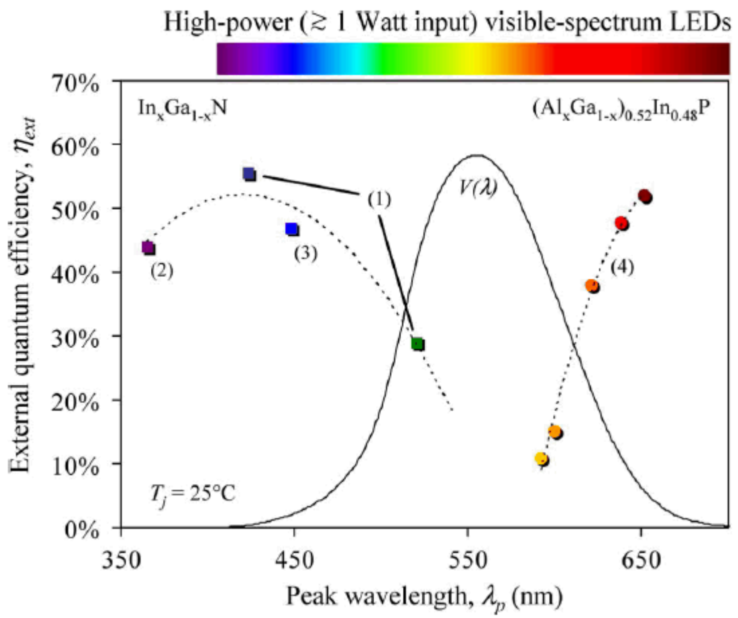




- Simulation of 415nm LD pumping 3 phosphors
  - 450 nm, 518 nm, and 637 nm
- Just like violet PC-LED solution, the violet PC-LD could also produce high color rending white light.

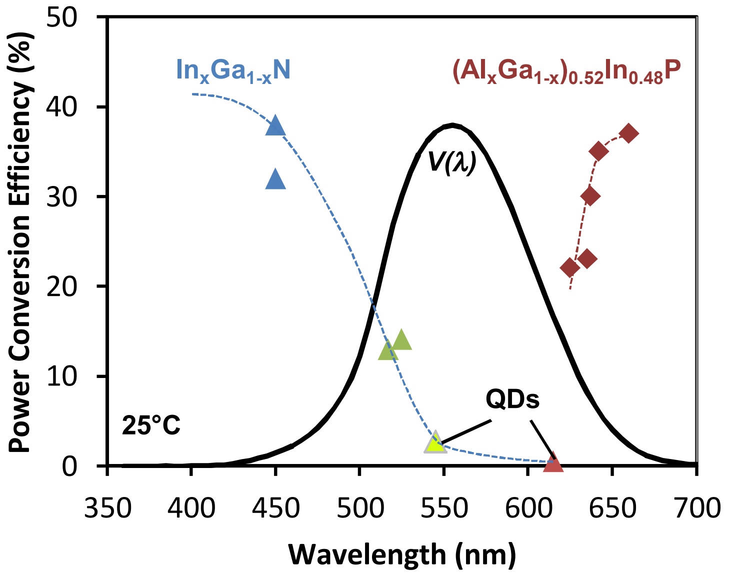
Direct emitters to produce white

LEDs



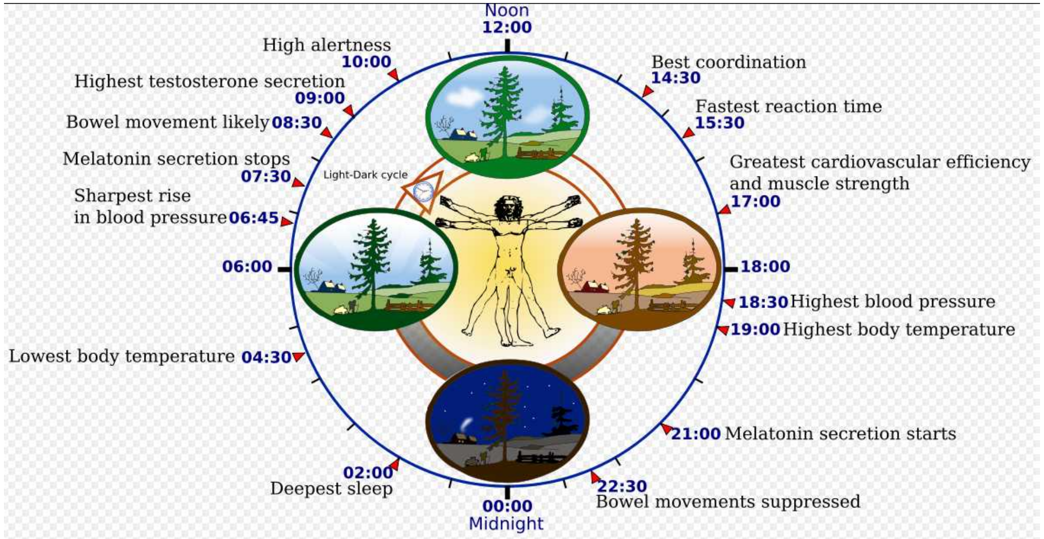
Krames, et al., IEEE J. Display Tech., June 2007

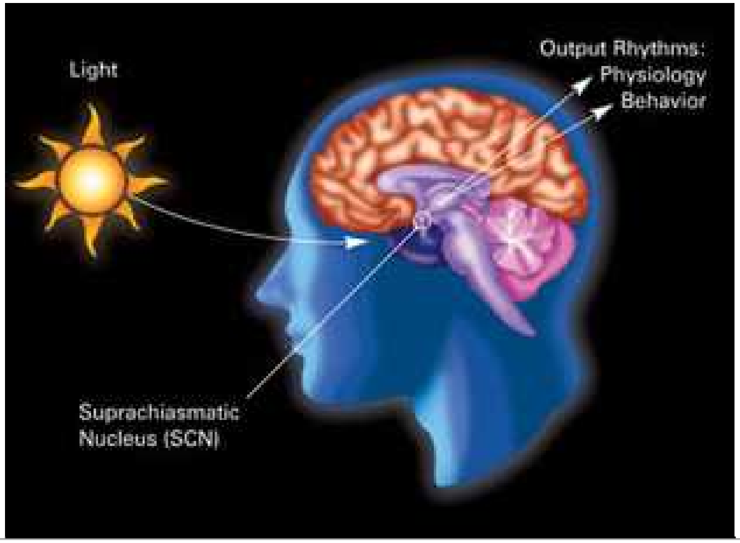
LDs

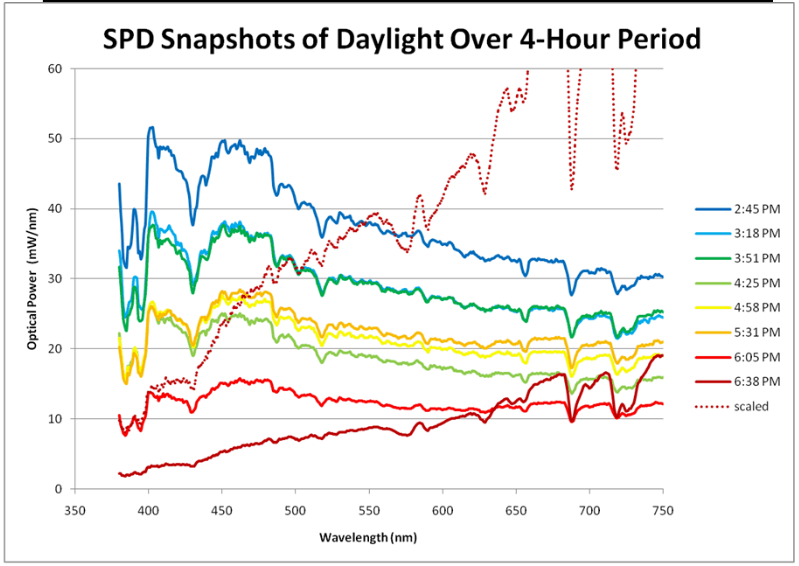


- Both LEDs and LDs suffer from the "green gap" problem.
- This limits the progress in white sources produced from direct emitters.

Managing human circadian rhythms



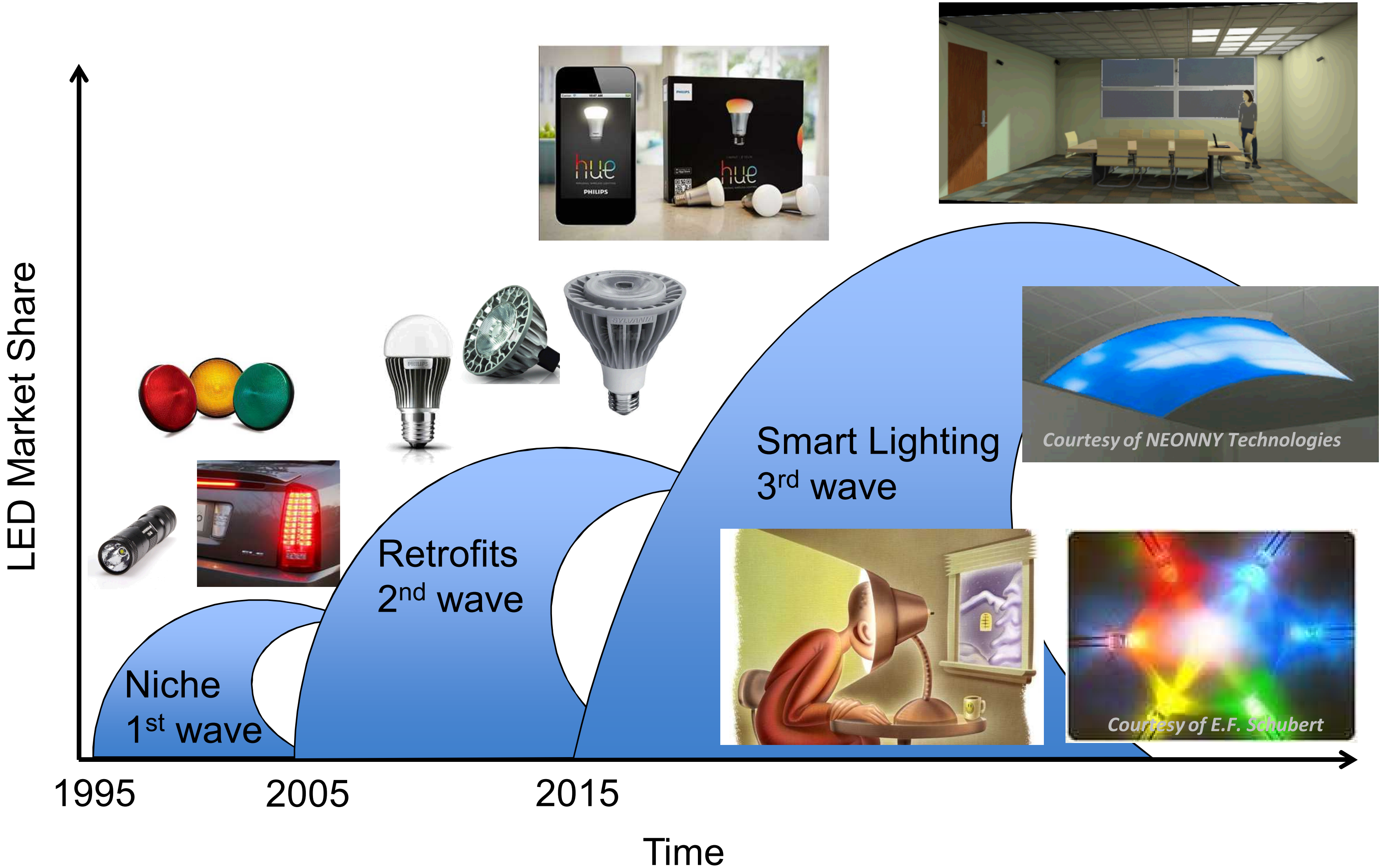




Recorded on Mt. Hamilton, CA at Lick Observatory– courtesy S. Paolini, CTO, Telelumen

- Circadian rhythms: physical, metal, and behavioral changes on a 24 hr. cycle.
- Circadian rhythms can influence sleep-wake cycles, hormone release, body temperature, and other important body cycles.
- Smart lighting will include chromaticity tuning to change color temperature during the day and ensure normal rhythms.

Market waves of LED lighting



* Inspired by Brian Chemel, CTO, Digital Lumens

LD system benefits

Luminance of PC-LEDs and PC-LDs

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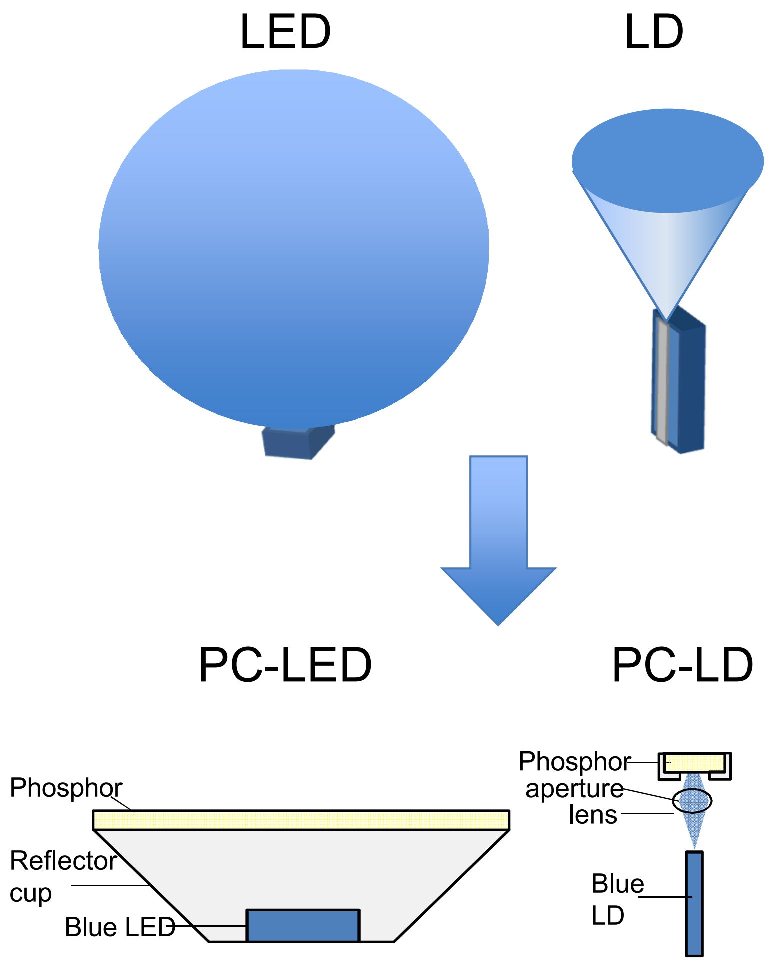

	PC-LED	PC-LD
Power (lm)	325	500
Phosphor emitting area (cm²)	0.09	0.01
Emitting half angle (°)	45	45
Luminous intensity, I_v, (lm/sr)	180	270
Illuminance, E_v, (lm/cm²)	3600	50000
Luminance, L_v (lm/sr/cm²)	1900	27000

- PC-LD benefits:
  - Beam can be focused and a much smaller phosphor volume can be used.
  - Smaller phosphor leads to higher luminance.
  - Smaller luminaires.

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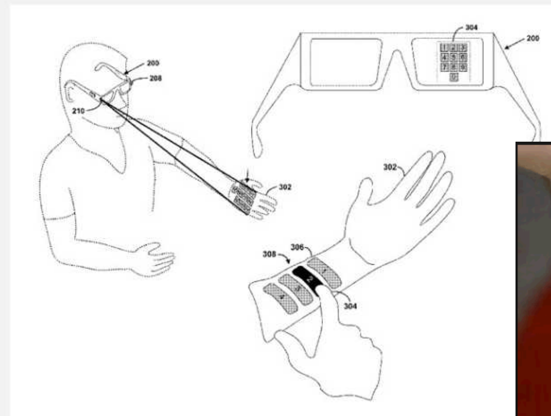
Laser diode micro-projectors


Google dreams up tiny laser projection system to control Project Glass

By **Sharif Sakr** posted Jan 17th, 2013 at 8:09 AM

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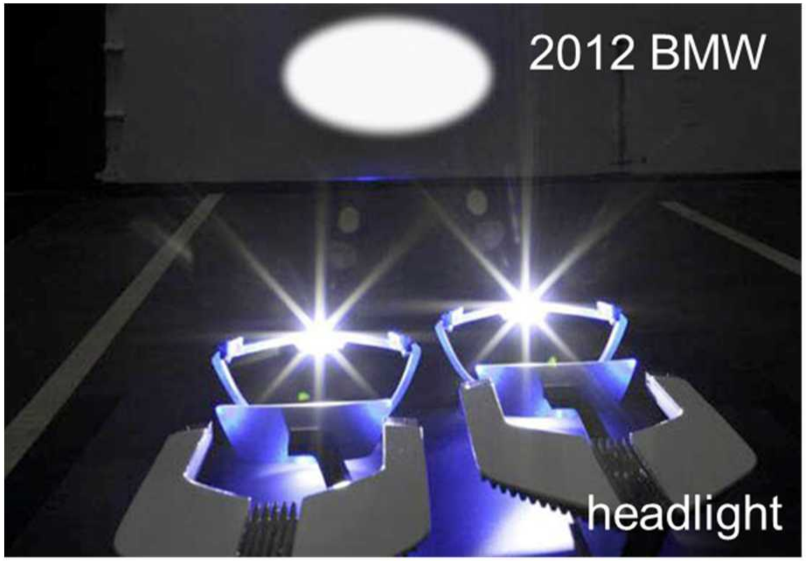
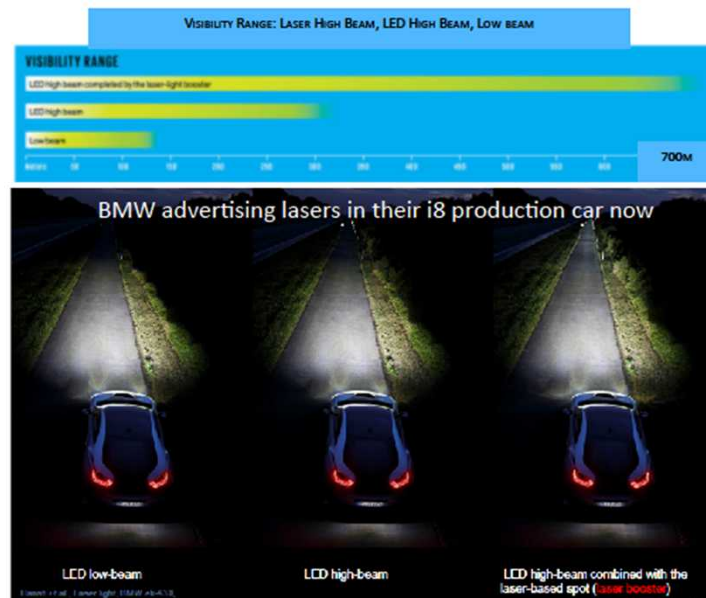
High luminance laser headlights

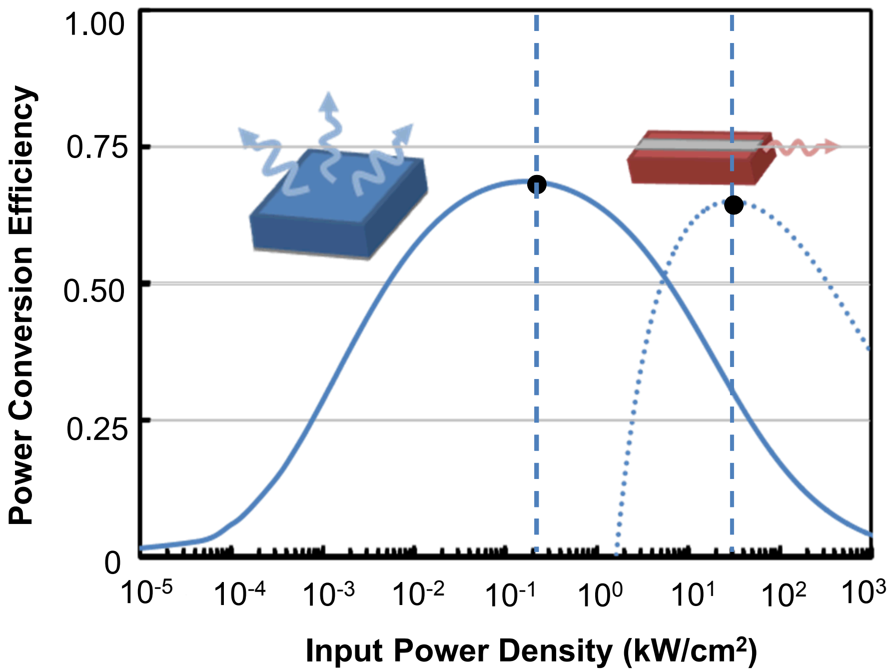


- Can deliver white light over longer distances.
- Example is BMWs laser headlights.



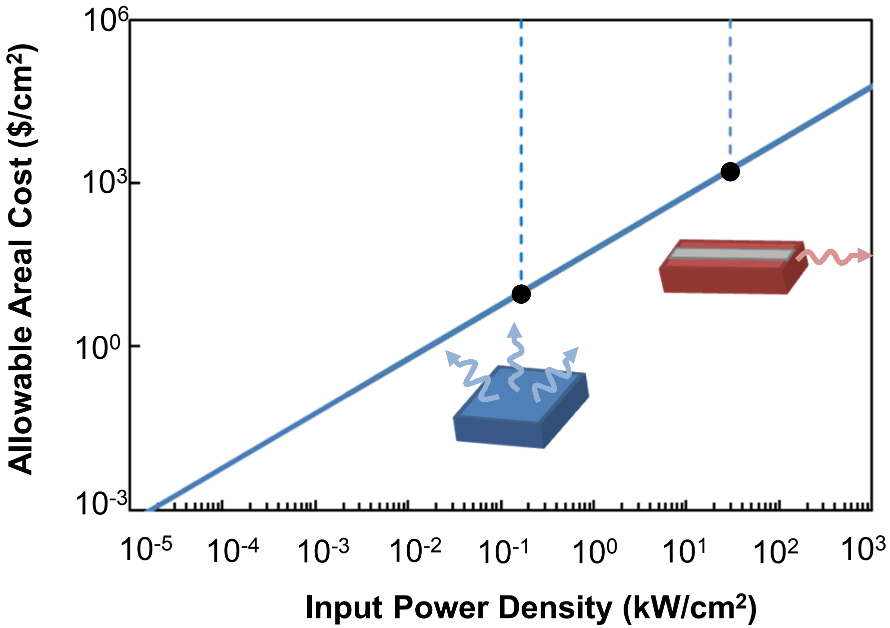
Economic comparison of LEDs and LDs

Economics of LEDs and LDs



- Assume a simple heat sink geometry.
- Assume operation is at peak efficiency.
- Input power density is different for LEDs and LDs.
- Two different input powers will drive different chip size and cost.

Economics of LEDs and LDs



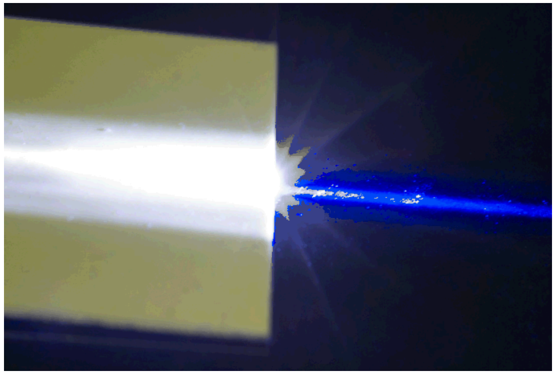
- Calculate the allowable areal cost.
  - Includes heat sink limited area and flux, and the capital and operating cost of light.
- Two vastly different areal costs.
  - LED: ~$10/cm^2
  - LD: ~$2000/cm^2
  - IR LDs are at ~$150/cm^2

Conclusion

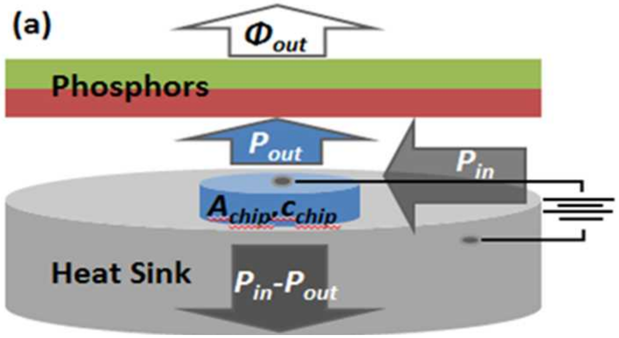
- LDs are not affected by efficiency droop after threshold.
    - LDs have higher efficiencies at higher input powers.
    - Modeling suggests LD peak efficiency could match LEDs.
- PC-LDs produce white light with color rendering and temperature similar to LEDs.
- LDs white sources have higher illuminance.
    - Smaller sources that can be projected farther.
- LDs small areas and higher output powers make them economically viable.

Work was supported by Sandia's Solid-State-Lighting Science Energy Frontier Research Center, funded by the U.S. Department of Energy, Office of Basic Energy Sciences.

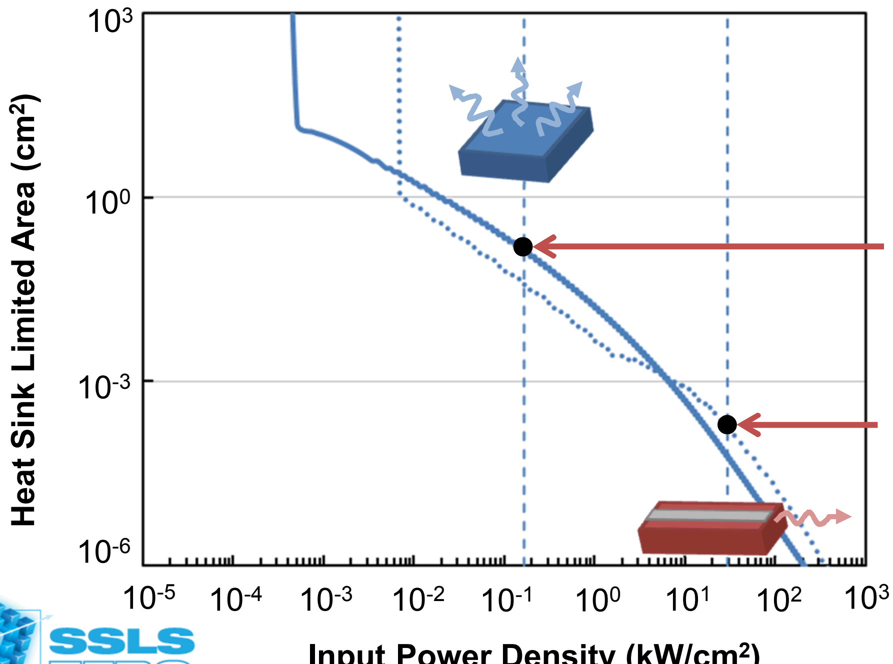
Thanks to D. Sizov at Corning Inc. for his contribution on LD efficiency modeling.



Economics of LEDs and LDs



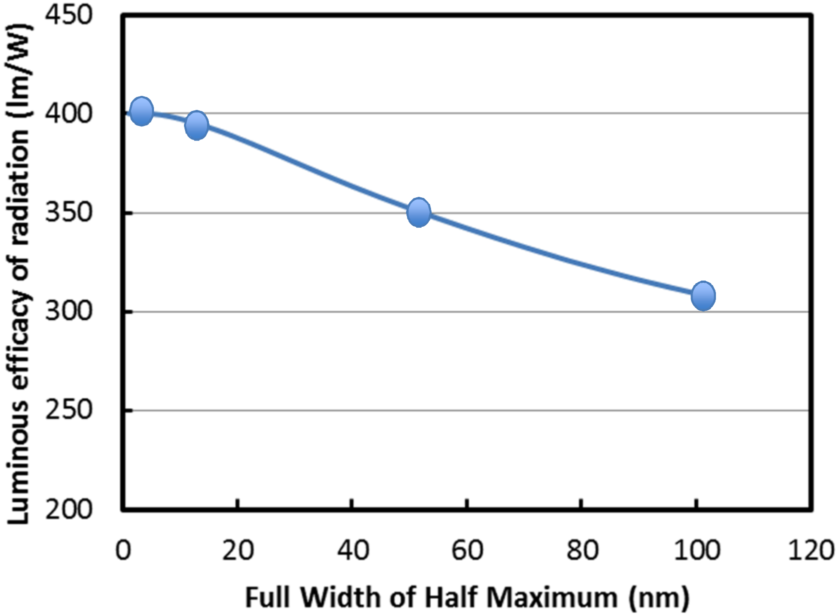
- Assume a simple heat sink geometry.
- Single light-emitting device.
- Calculate the heat-sink-limited area.
  - Maximum chip area compatible with a particular input power density, power-conversion efficiency and maximum allowable temperature rise

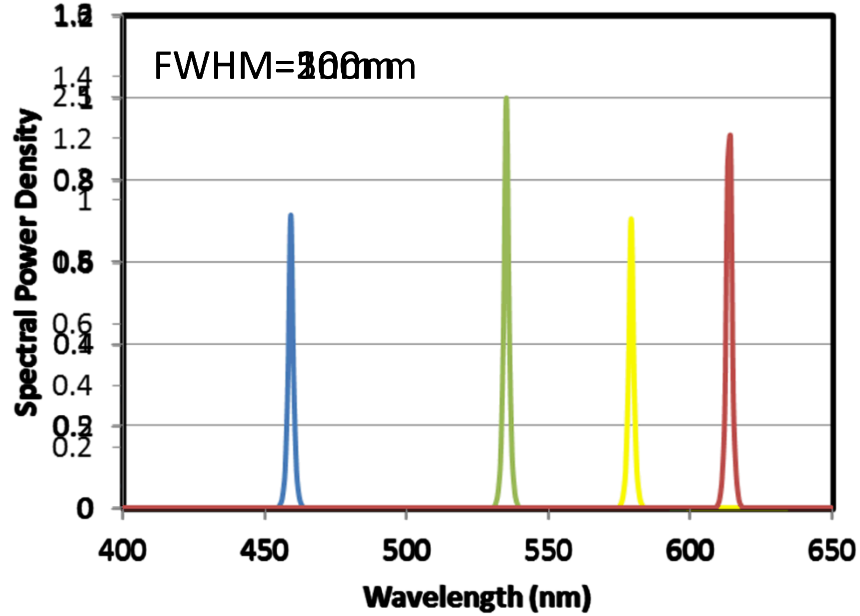


LED~0.14 cm^2 = 0.37cm x 0.37cm

LD~1.6×10^{-4} cm^2 = 16um x 1mm stripe

High Luminous efficacies of radiation





- Spiky sources give highest luminous efficacies of radiation (lm/W)
- Red/yellow power varied to give CCT=3800, Ra=85