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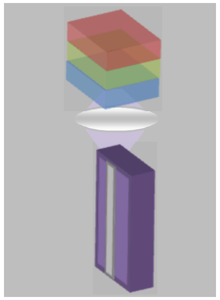
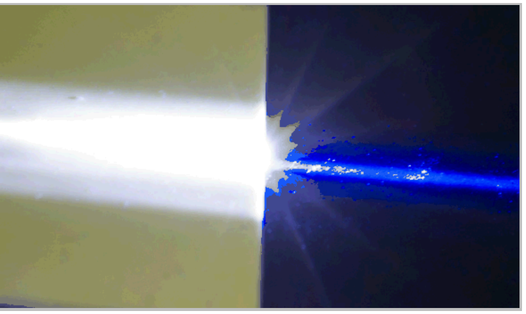




Opportunities for laser diodes in solid-state lighting

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

**jwierer@sandia.gov*

Sandia National Laboratories

Exceptional service in the national interest

CS International, Frankfurt, Germany   11th March 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

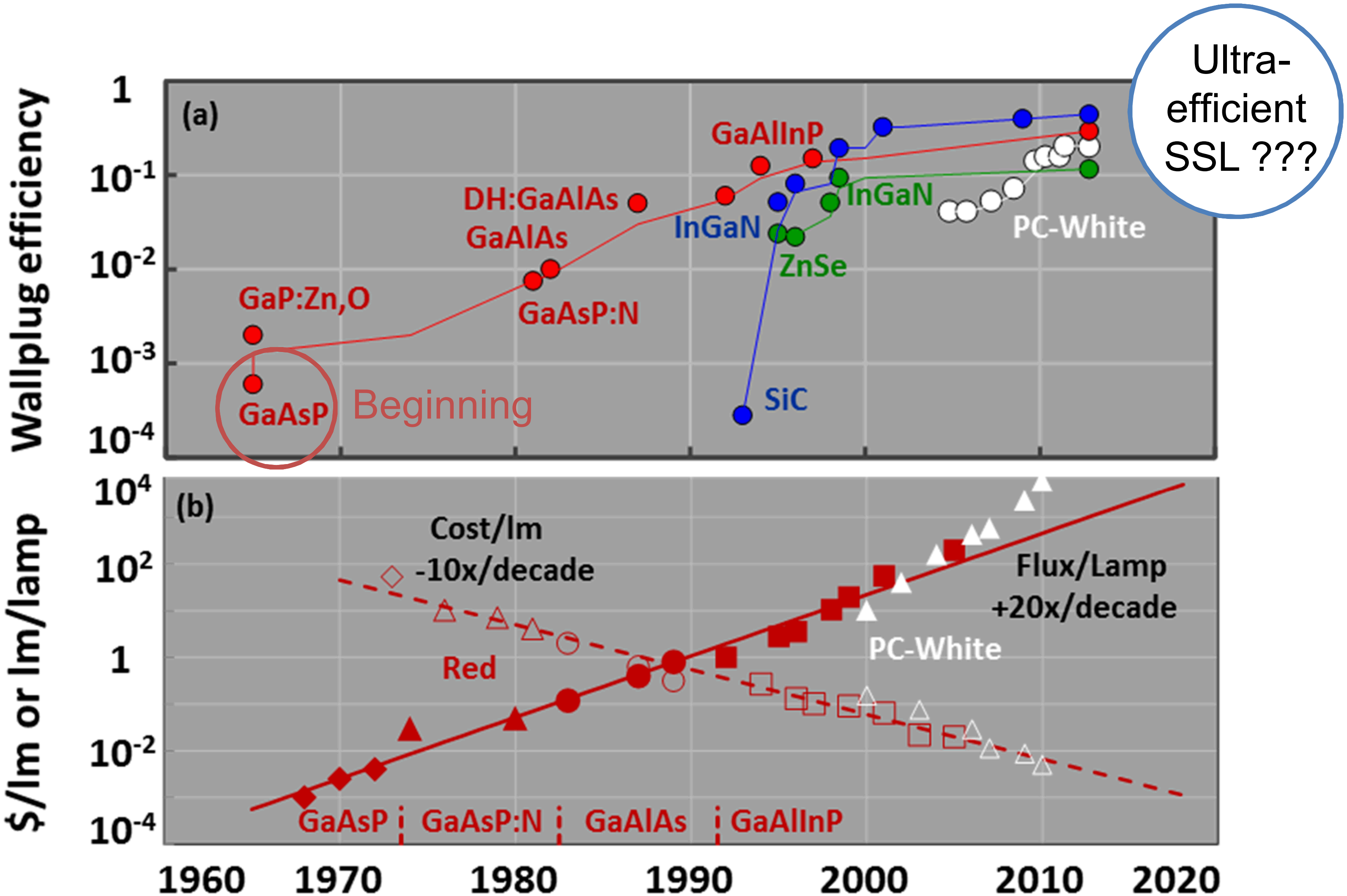
SSLS EFRC

Outline

- Some solid-state lighting history.
- Efficiency comparison and projections for blue LEDs and laser diodes (LDs).
- White light from LDs.
- LD system benefits.
- Economically is ultra-efficient solid-state lighting worth pursuing?

Some solid-state lighting history

LED efficiency and cost over time



Nick Holonyak, Jr. :inventor, visible LED

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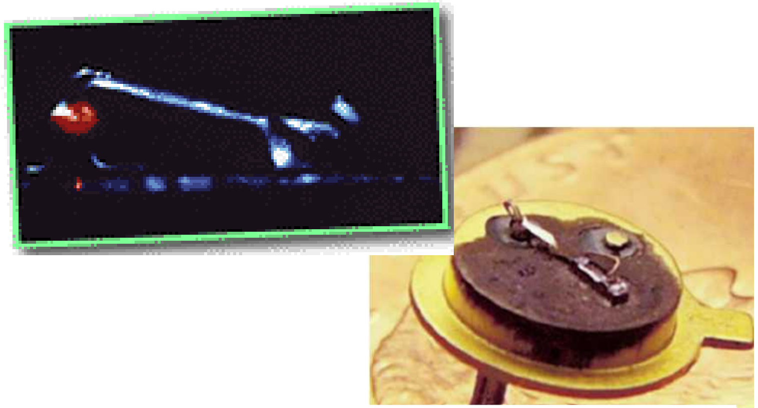
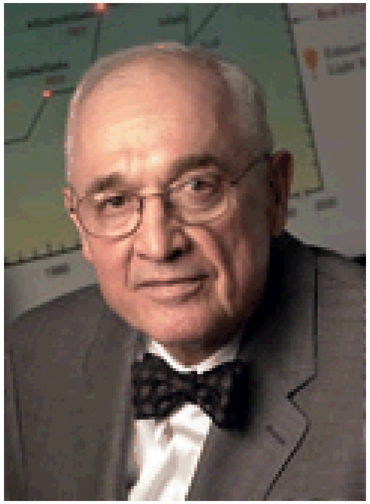
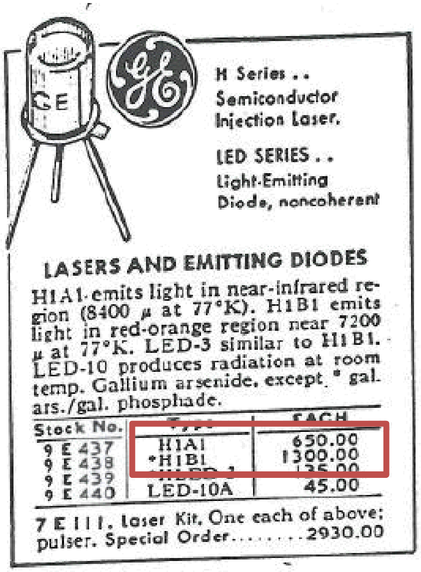





H Series . . Semiconductor Injection Laser.

LED SERIES . . Light-Emitting Diode, noncoherent

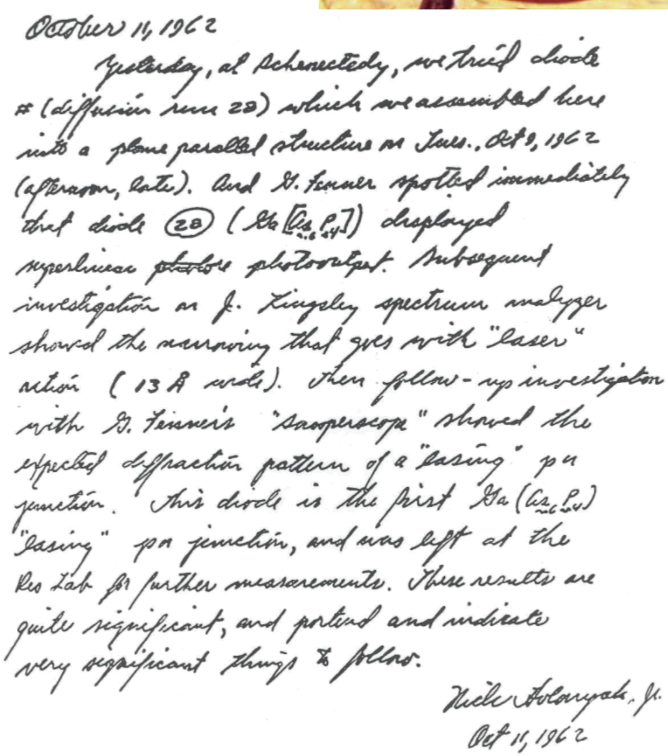
LASERS AND EMITTING DIODES

H1A1 emits light in near-infrared region (8400 μ at 77°K). H1B1 emits light in red-orange region near 7200 μ at 77°K. LED-3 similar to H1B1. LED-10 produces radiation at room temp. Gallium arsenide, except * gal. ars./gal. phosphade.

Stock No.	Type	Each
9 E 437	H1A1	650.00
9 E 438	*H1B1	1300.00
9 E 439	[illegible]	[illegible]
9 E 440	LED-10A	45.00

7 E 111. Laser Kit. One each of above; pulser. Special Order........2930.00

1965 Allied Radio Catalog


October 11, 1962

Yesterday, at Schenectady, we tried diode # (diffusion run 28) which we assembled here into a plane parallel structure on Tues., Oct 9, 1962 (afternoon, late). And G. Fenner spotted immediately that diode (28) (Ga[As1-xPx]) displayed superlinear ~~photo~~ photooutput. Subsequent investigation on J. Kingsley spectrum analyzer showed the narrowing that goes with "laser" action (13 Å wide). Then follow-up investigation with G. Fenner's "snooperscope" showed the expected diffraction pattern of a "lasing" pn junction. This diode is the first Ga(As1-xPx) "lasing" pn junction, and was left at the Res Lab for further measurements. These results are quite significant, and portend and indicate very significant things to follow.

Nick Holonyak, Jr.
Oct 11, 1962

- First visible laser in Oct of 1962.
- Made from Gallium Arsenide Phosphide (GaAsP).
- A working laser diode suggested light producing efficiency was high.
- Further suggests efficient LED.

Light of Hope – Or Terror

Sandia National Laboratories

February 1963 Reader's Digest 35¢

Light of Hope– Or Terror?

The present and potential uses of the laser—a new kind of light ray—sound like science fiction. In fact, the invention is one of the most amazing accomplishments of our time

By Harland Manchester

One evening last May, a thin streak of red light shot through space from the roof of M.I.T.'s Lincoln Laboratory at Lexington, Mass., hit the moon (then 250,000 miles away), and bounced back to an instrument which recorded its pioneering round trip. The light came from a new kind of electric torch, called a "laser," which emits a slender pencil of regimented light unlike anything known before. The beam of an ordinary searchlight aimed at the moon would fan out to a circle 25,000 miles wide; its reflection would be too faint to record. The laser beam made a dot only two miles across.

Laser stands for "light amplification by stimulated emission of radiation." Its invention is one of the most exciting events of this century. Since the new light first appeared three years ago, some 400 firms and universities have launched laser research projects, and an estimated 30 million dollars was spent last year in experimentation. Still in its early development stage, the laser prom-

Harland Manchester, a Roving Editor of The Reader's Digest, has specialized in reporting developments in the field of science for many years. His latest book, *Trail Blazers of Technology*, was published last November by Charles Scribner's Sons.

a TV broadcast from the air and beaming it by invisible infrared light 275 feet to a receiver, with good reception. The bit of metal alloy they used was not a laser, for it did not comb the tangles out of the light beam, but its performance sparked a tremendous research drive. Last fall several outfits, including General Electric, IBM, RCA and Lincoln, produced metal lasers which emit "coherent" or tuned light. These appear to be destined for a great future in the communications field.

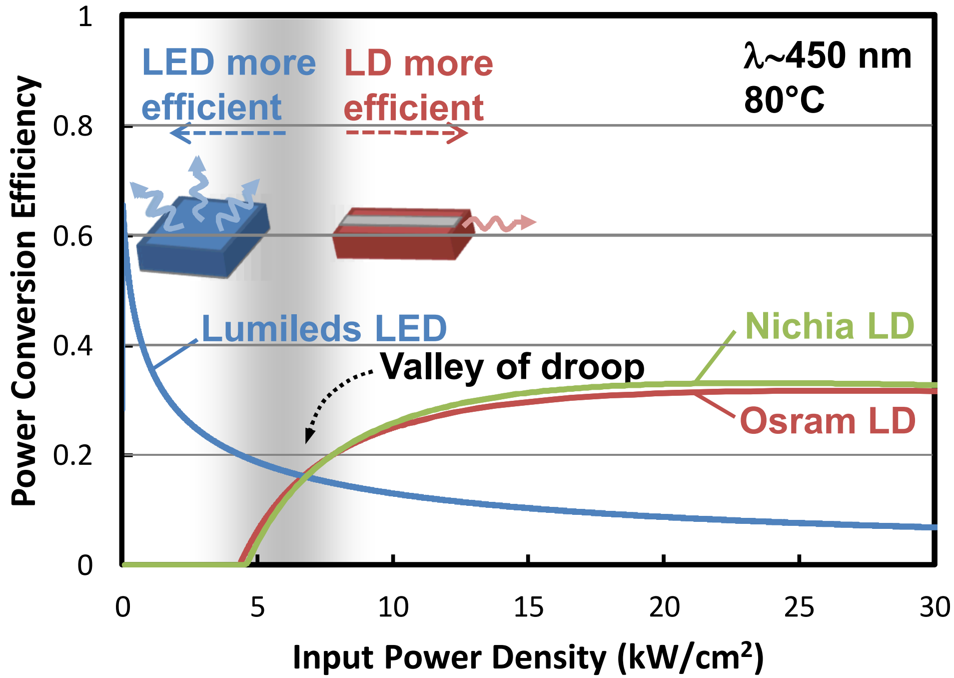
The latest dramatic laser discovery, made by General Electric, may someday make the electric light bulb obsolete. While the radiation from previous lasers was invisible, this one emits *visible* light in the red region of the spectrum. Research is continuing, and GE engineers hope to build lasers which will convert ordinary electric current into white light with a high degree of efficiency.

"We believe there is a strong possibility of developing the laser as a practical light source," says Dr. Nick Holonyak, head of General Electric's Advanced Semiconductor Laboratory. "Much more experimental work must be done, and it might be ten years or more before such a lamp could be ready for wide use. However, within a year we should have them ready for computer indicators and many other electronic devices, where they should be very useful because of the small size, and speed of action."

If these plans work out, the lamp of the future may be a speck of metal the size of a pencil-point which will be practically indestructible, will never burn out, and will convert at least ten times as much current into light as does today's bulb.

Efficiency comparison and projections of LEDs and LDs

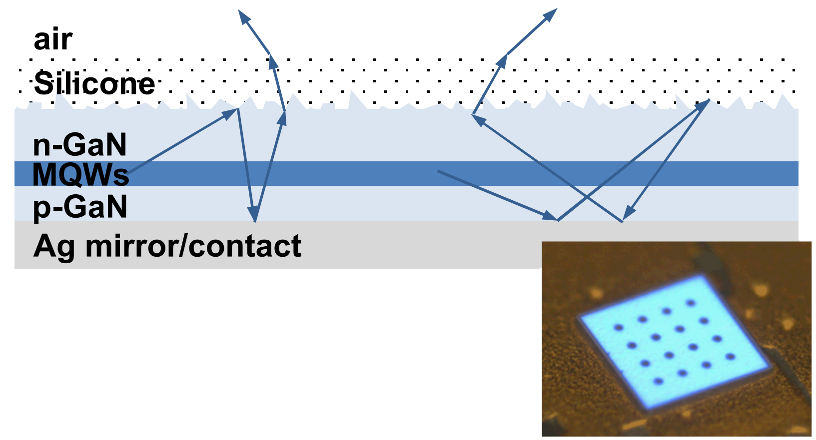
III-nitride blue LEDs vs. LDs



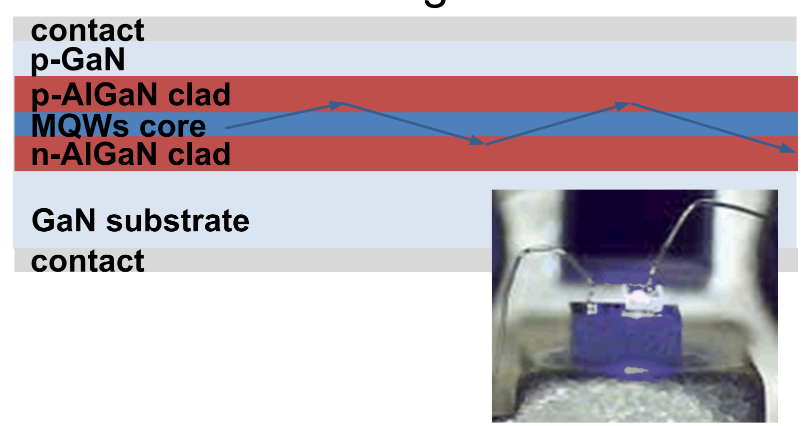
J. J. Wierer, Jr., D. S. Sizov, and J. Y. Tsao, *"Comparison between Blue Laser and Light-Emitting Diodes for Future Solid-State Lighting"*, Laser and Photonics Review (2013).

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

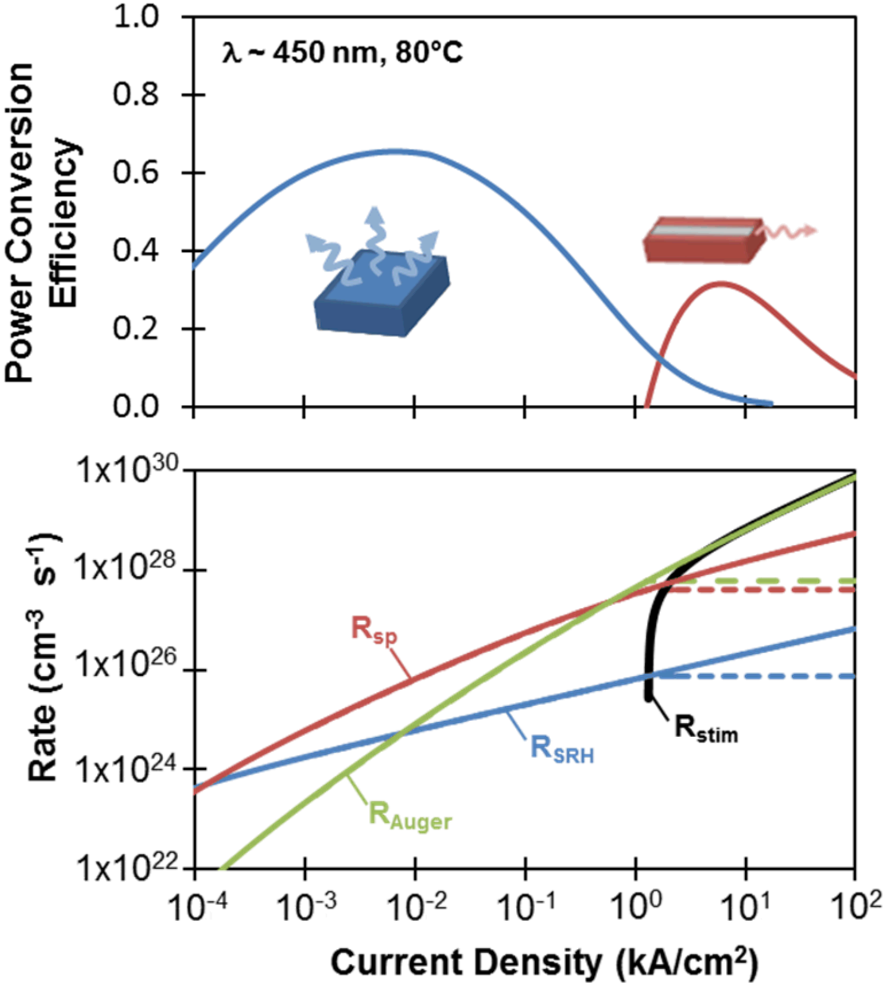
Blue LED: thin-film



Blue LD: edge-emitter



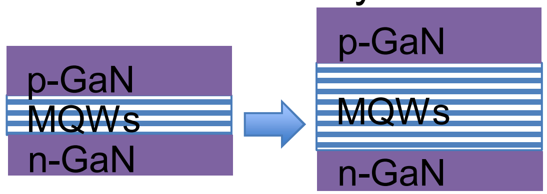
Physics



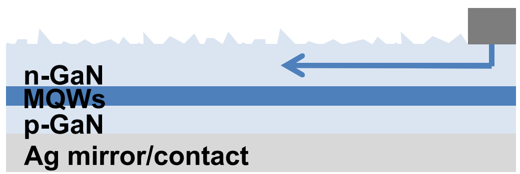
- Recombination processes determine efficiency.
- $R_{total} = R_{SHR} + R_{Sp} + R_{Auger} + R_{stim}$
- *LED:*
  - $\eta_{rad} = R_{sp} / (R_{SRH} + R_{sp} + R_{Auger})$
  - $R_{stim} = 0$
- LD:
  - $R_{SHR} + R_{Sp} + R_{auger}$ *are fixed, and* R_{stim} *grows after threshold.*
- Method to circumvent efficiency droop.

Potential LED improvements

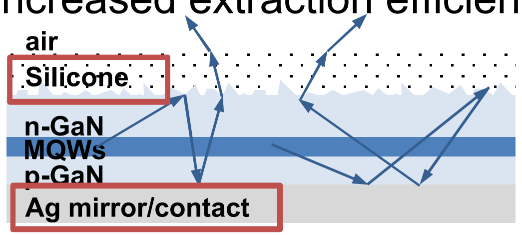
- Increased active layer thickness:



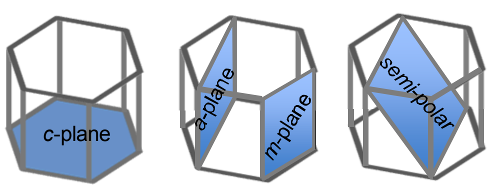
- Reduced series resistance:

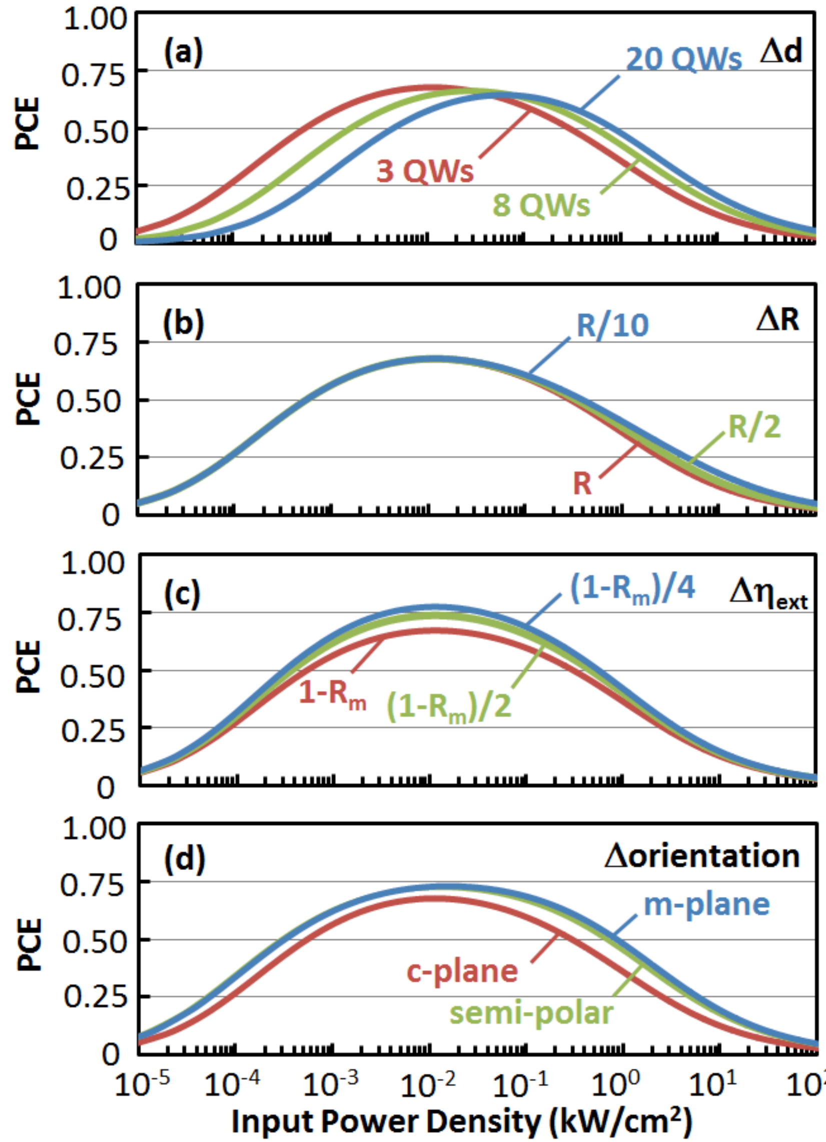


- Increased extraction efficiency:



- Change crystal orientations:

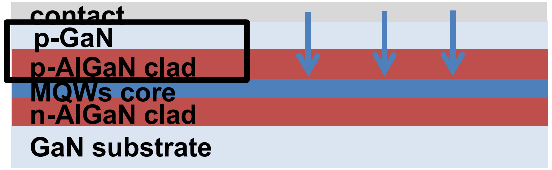




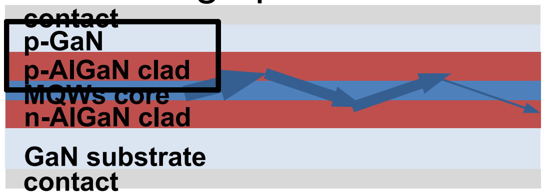
2

Potential LD improvements

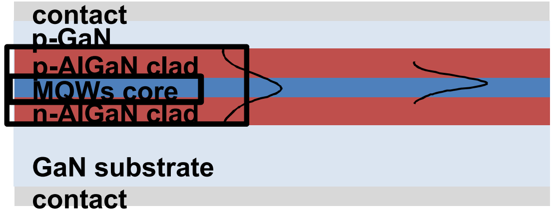
Reduced series resistance:



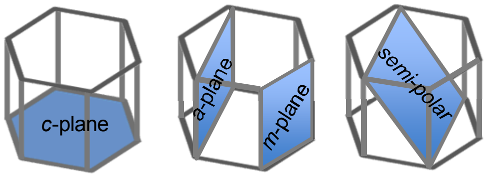
Decreasing optical loss:

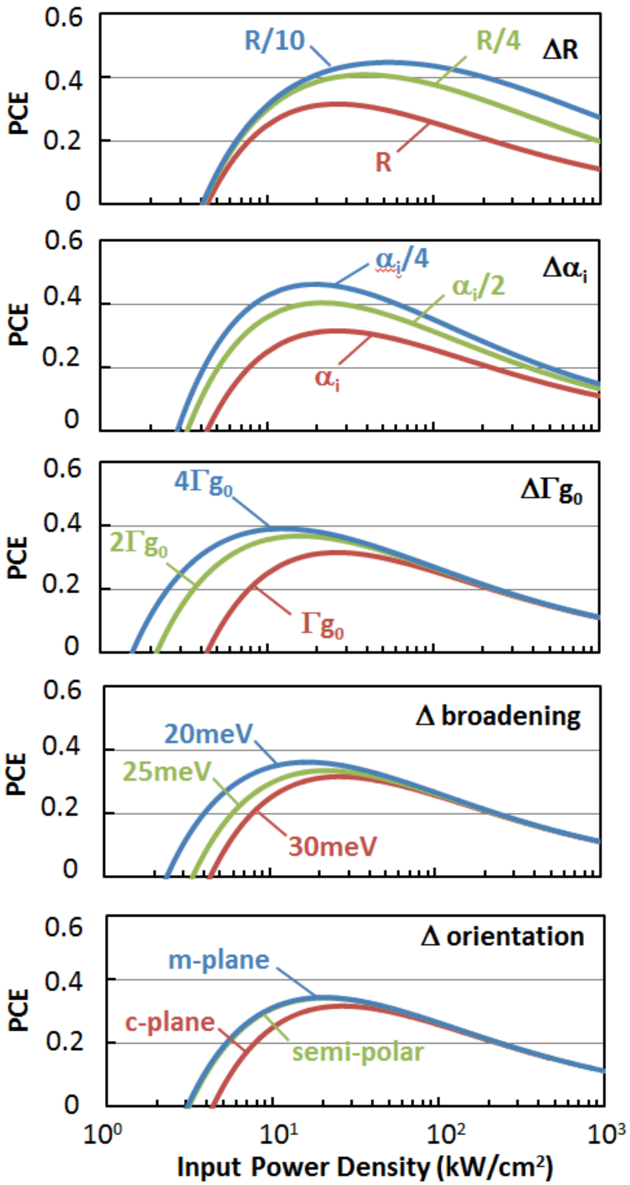


Increasing modal gain:

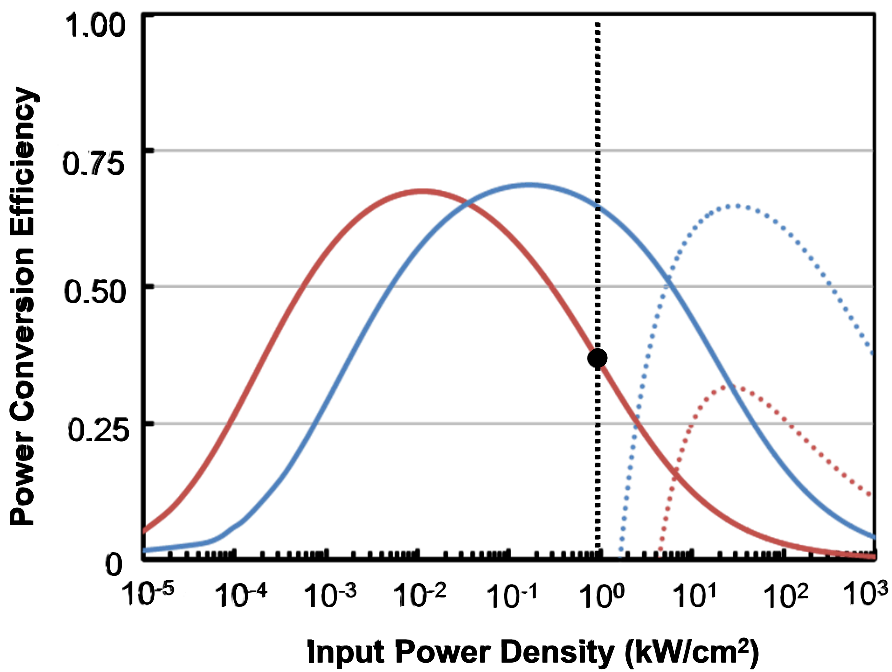


Change crystal orientations:





Projection of efficiency improvements



LED

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

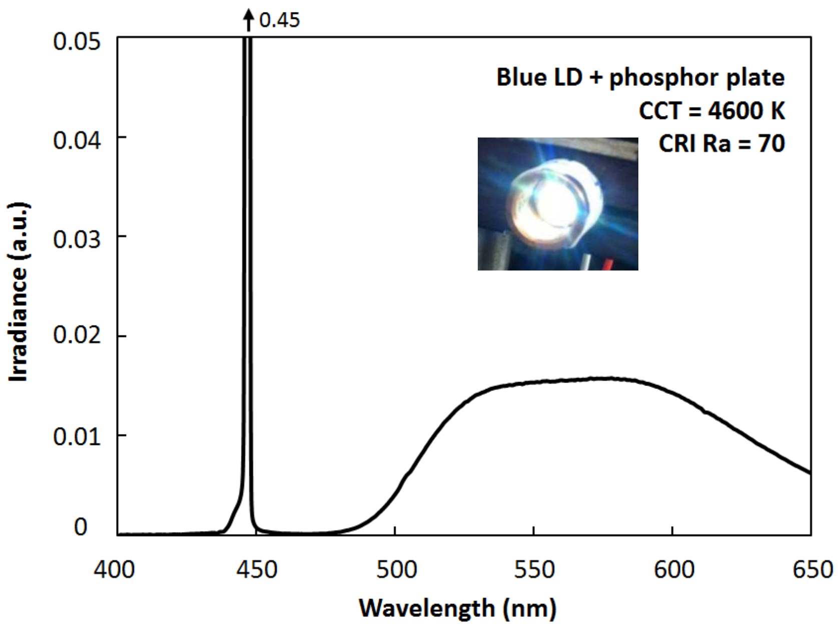
LD

	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

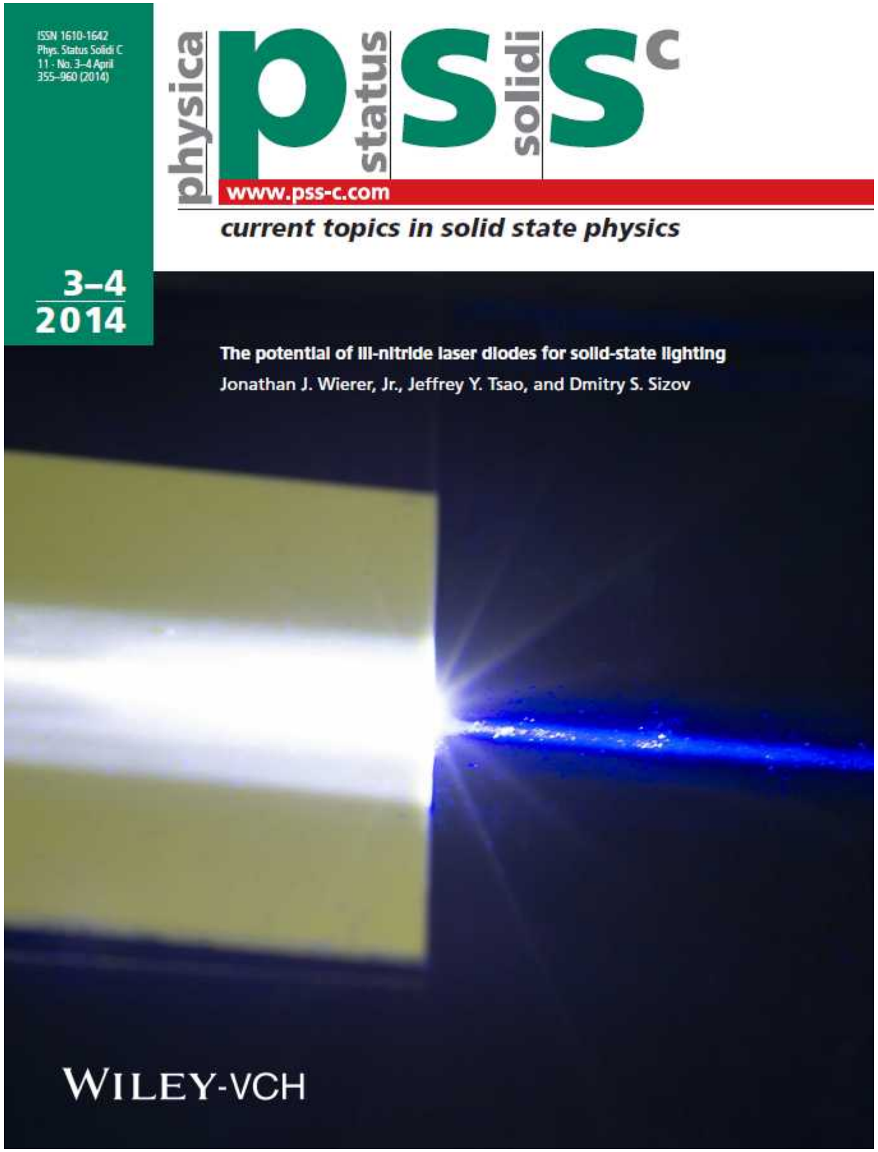
- Blue LD has the potential to have similar peak efficiencies as LEDs, but at much higher output powers.

White light from LDs

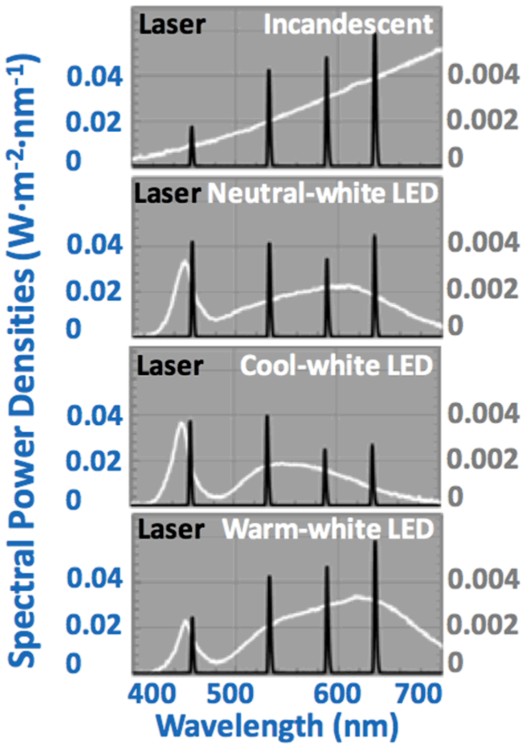
Phosphor converted LD (PC-LD) white

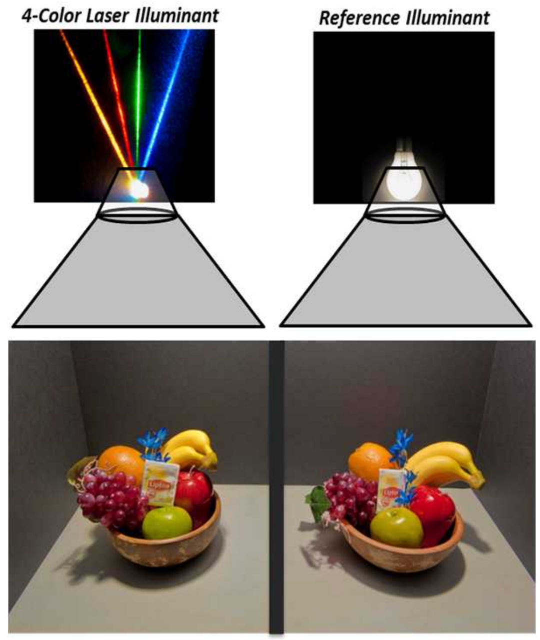


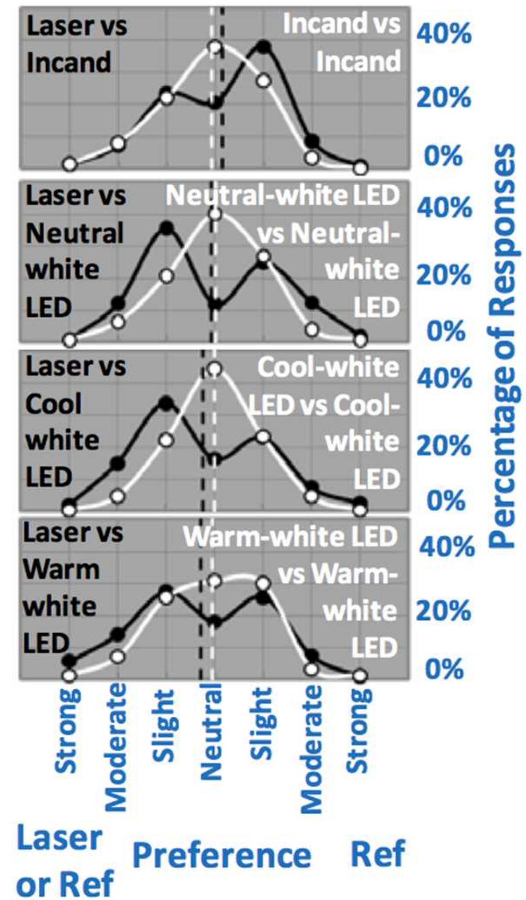
- Commercial blue LD + ceramic phosphor.
- Color temperature and rendering are comparable to PC-LED.
- Blue LDs can be used to produce white light.



Laser white color rendering



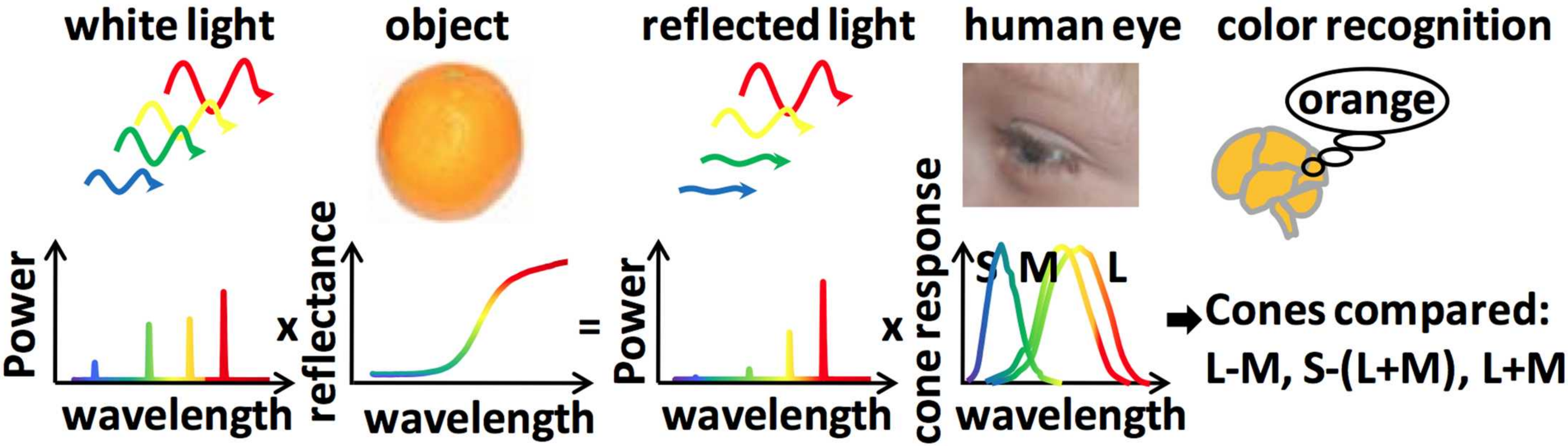




A. Neumann, J. J. Wierer, Jr., W. Davis, Y. Ohno, S. R. J. Brueck, and J.Y. Tsao, Optics Express, 19, A982, 2011.

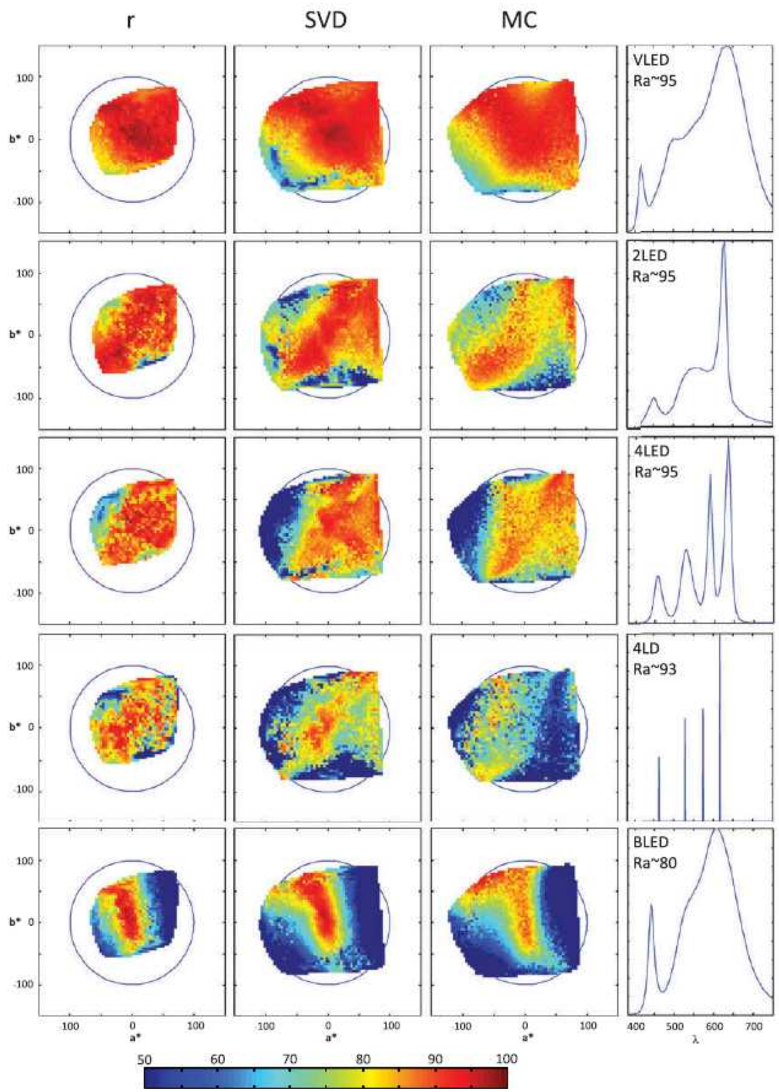
- Only slight preferences when comparing LD and traditional sources.
- LD white is a good color rendering source. Why?

Laser white color rendering



A. Neumann, J. J. Wierer, Jr., W. Davis, Y. Ohno, S. R. J. Brueck, and J.Y. Tsao, Optics Express, 19, A982, 2011.

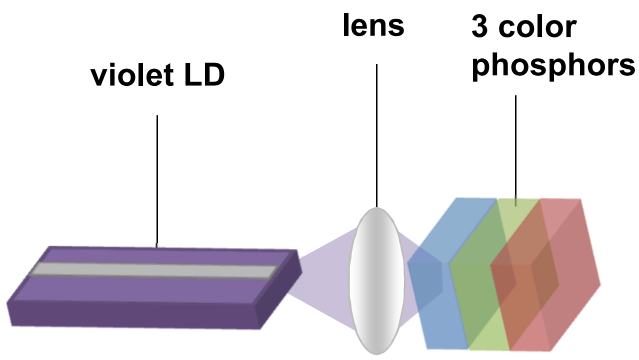
Color rendering over large data sets

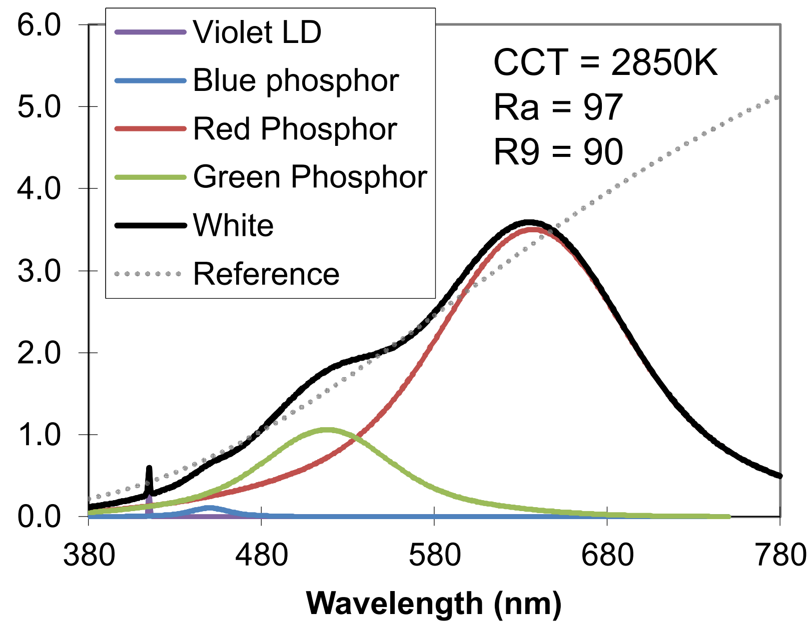


- Color rendering maps for five sources and three large data sets.
- Data sets:
  - r: real world
  - SVD: synthetic/expanded
  - MC: Monte Carlo randomly generated.
- In general, spectra without gaps have good color rendering over a wider gamut.
- So does this exclude lasers from solid-state lighting?

A. David, "Color fidelity of light sources evaluated over large sets of reflectance samples", LEUKOS, **10**, 59, 2014.

Violet pumped PC-LD

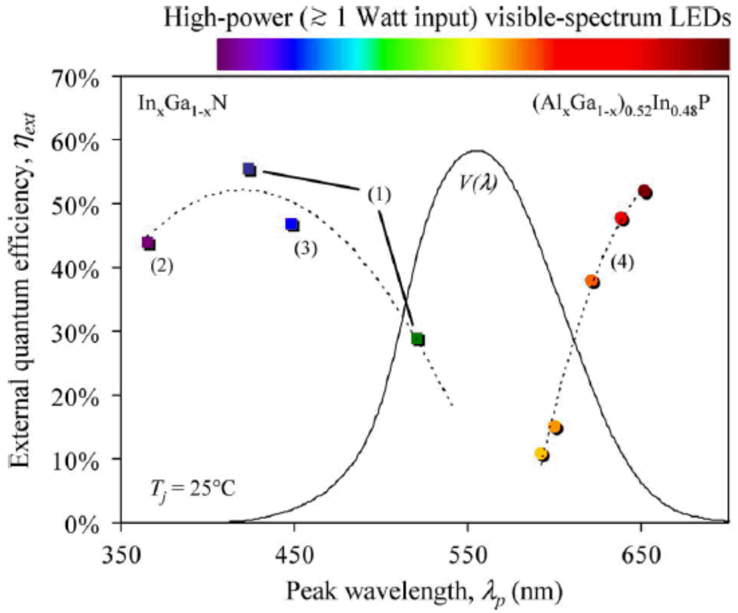




- Simulation of 415nm LD pumping 3 phosphors
  - 450 nm, 518 nm, and 637 nm
- Just like violet PC-LED solution, the violet PC-LD could also produce high color rending white light.
- Phosphor converted solutions cannot chromaticity tune.

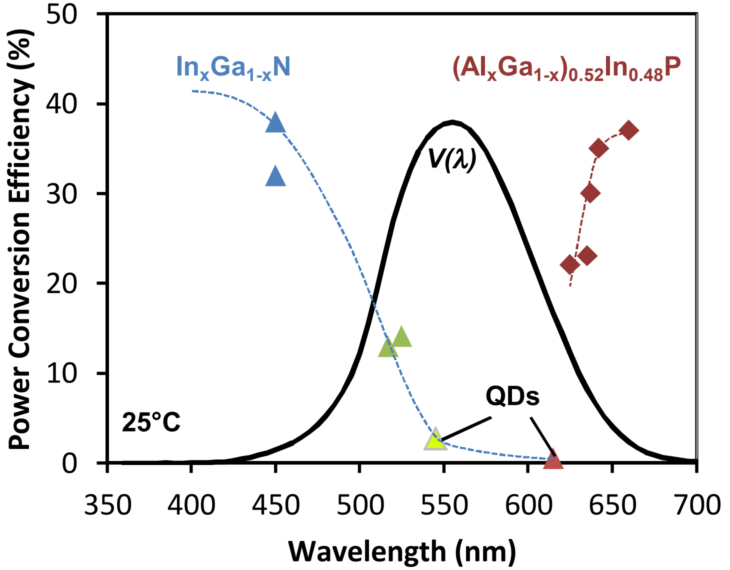
Direct emitters to produce white

LEDs



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

LDs

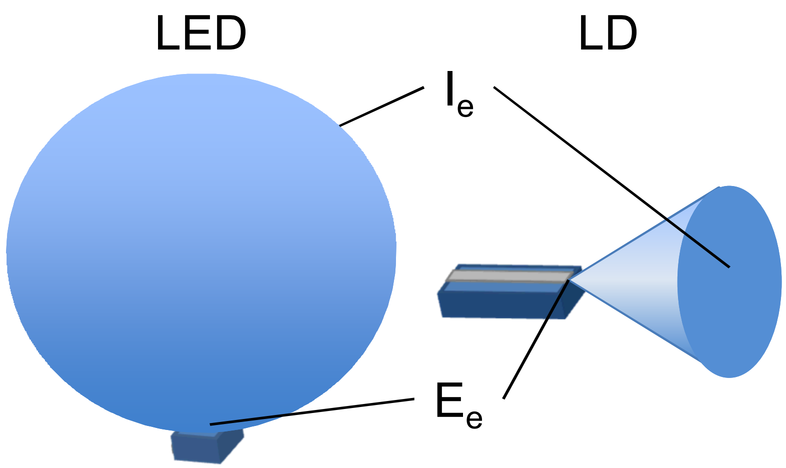


J. Wierer & J. Tsao., PSSA, 2015.

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

LD system benefits

Radiance of blue LEDs and LDs

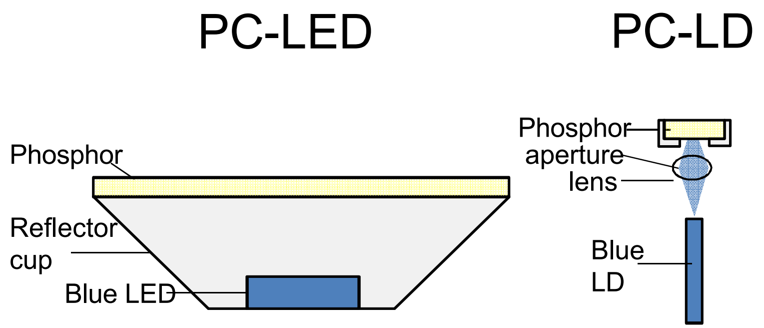


	Blue LED	Blue LD
Power (W)	1	1
Emitting area (cm^2)	1.00E-02	1.50E-07
Emitting half angle (°)	45	15
Radiance, L_e, ($W/sr/cm^2$)	54	3E+07

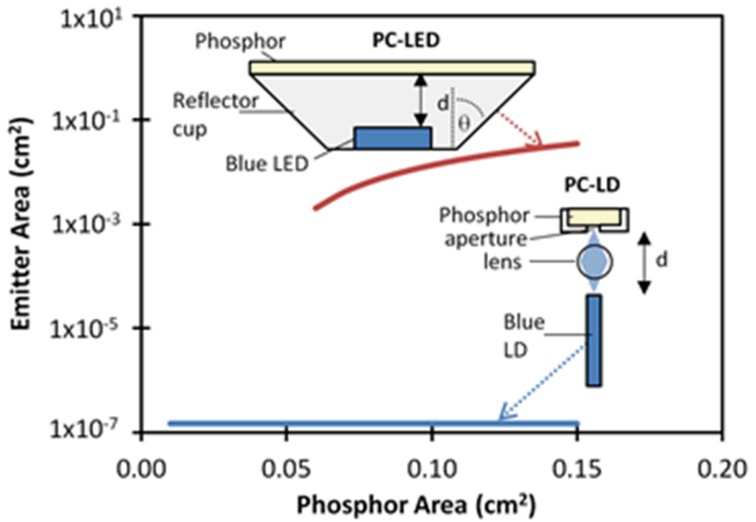
- LD benefits:
  - Irradiance (power density) is much higher in LDs.
  - Emission is directional
  - Emission is from a small aperture.
  - Superior for ètendue limited optical systems (i.e. projectors).

- These LD benefits produce a higher radiance source and advantages when creating a white source.

Luminance of PC-LEDs and PC-LDs

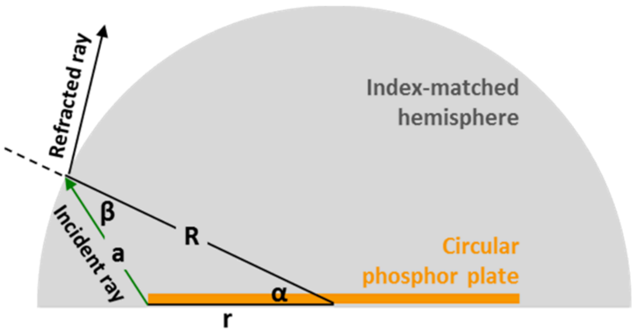


	PC-LED	PC-LD
Power (lm)	250	250
Phosphor emitting area (cm^2)	0.09	0.01
Emitting half angle (°)	45	45
Luminance, L_v ($lm/sr/cm^2$)	1500	14000



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

Comparison of LED and LD luminaires



	PC-LED	PC-LD
Phosphor emitting area (cm^2)	0.09	0.01
Radius of lens (cm)	0.225	0.075
Area of the lens (cm^2)	0.16	0.018

- What are the sizes of luminaires for PC-LD and PC-LED?
- Need to avoid total internal reflection from lens (Weierstrass condition):
  - R>rn, where n is index of the lens.
- For the PC-LD
  - Lens is 9 times smaller: microluminaire!

Market waves of LED lighting

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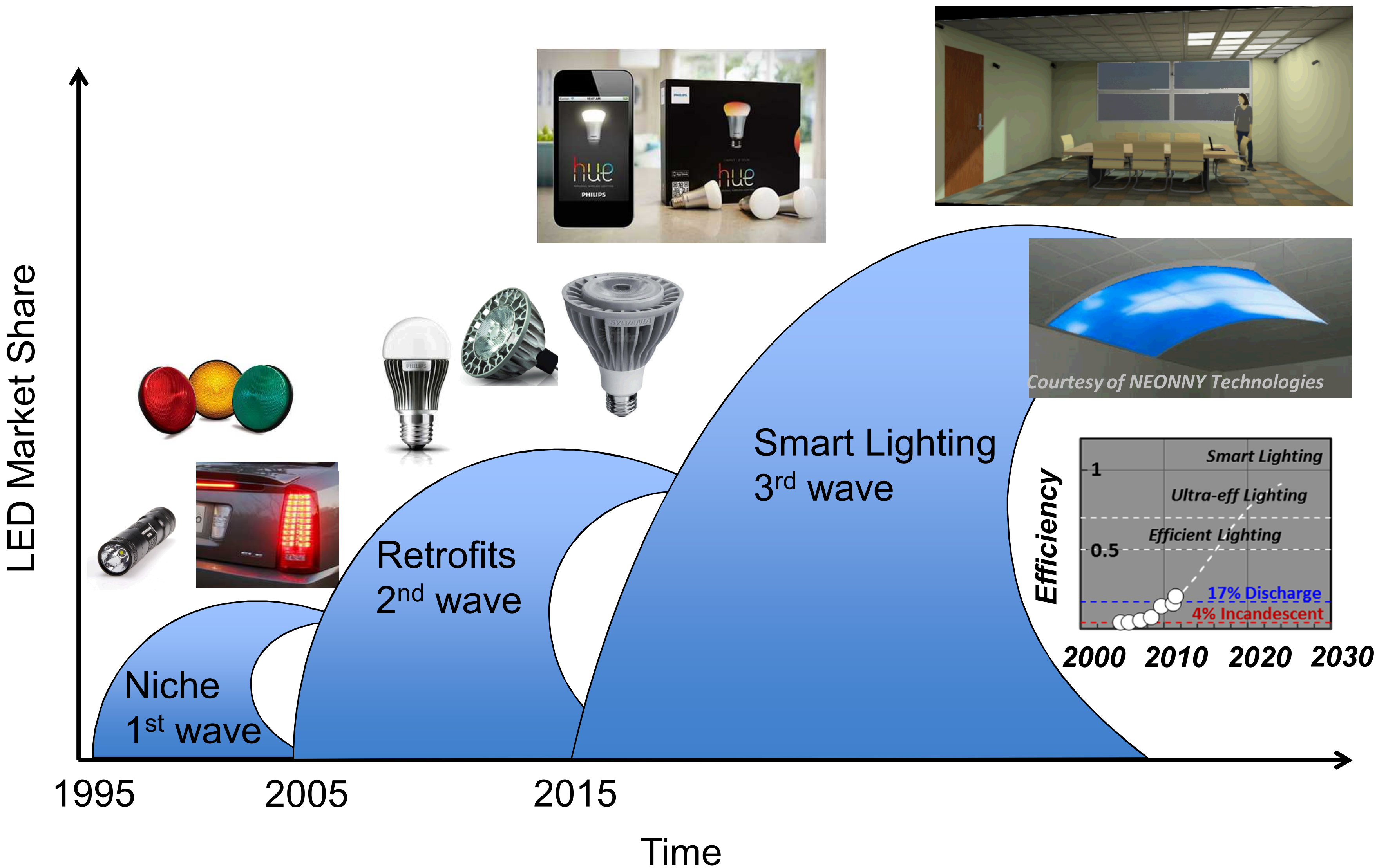


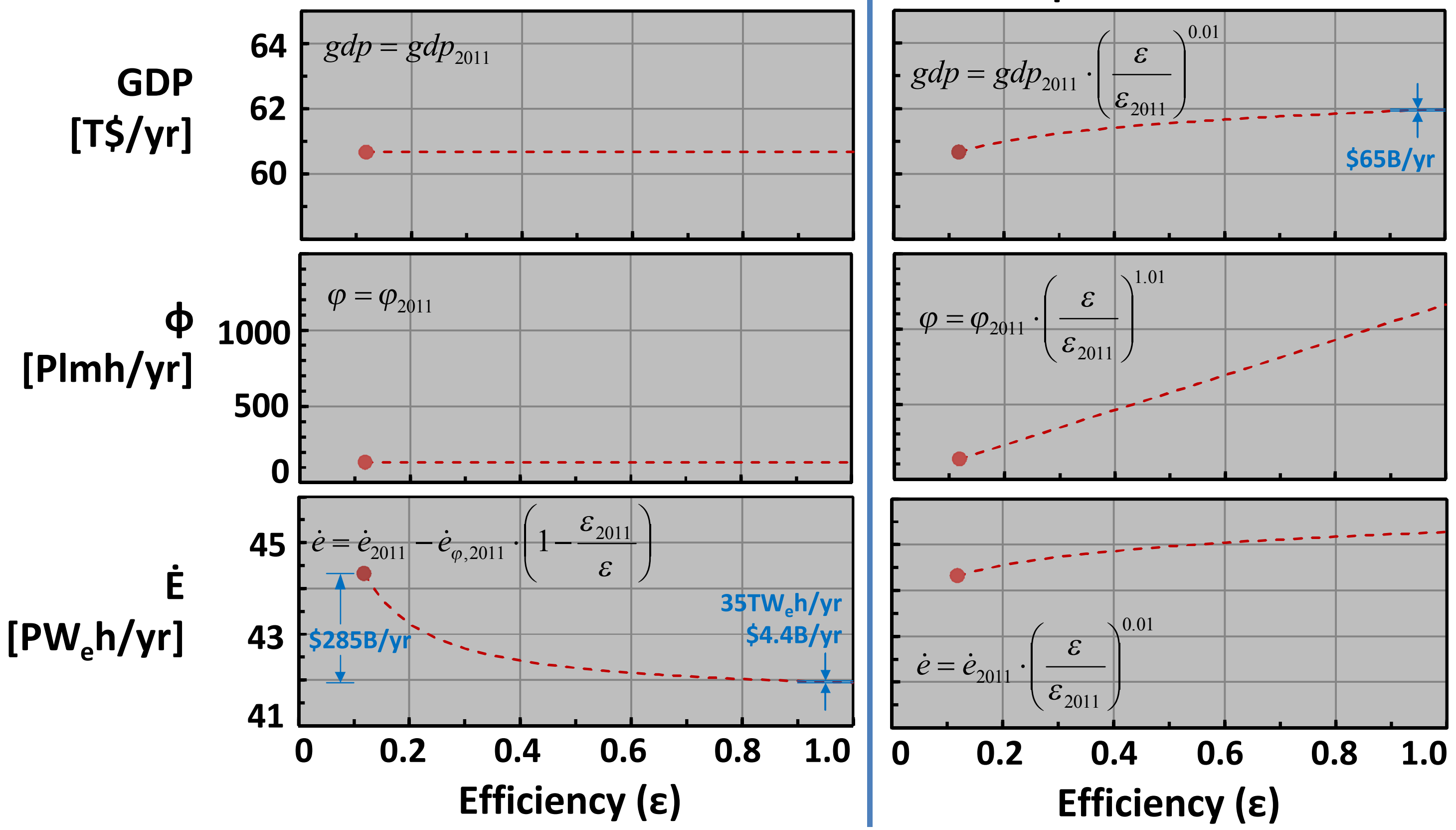
* Inspired by Brian Chemel, CTO, Digital Lumens

Economically is ultra-efficient SSL worth pursuing?

Is ultra-efficient SSL worth pursuing?

Light *isn't* an economic factor of production, and consumption is saturated

Light *is* an economic factor of production, and consumption isn't saturated



J.Y. Tsao, H.D. Saunders, J.R. Creighton, M.E. Coltrin and J.A. Simmons, "Solid-state lighting: an energy-economics peerspective," J. Physics D **43**, 354001 (2010).

A qualified yes: more light = more productivity

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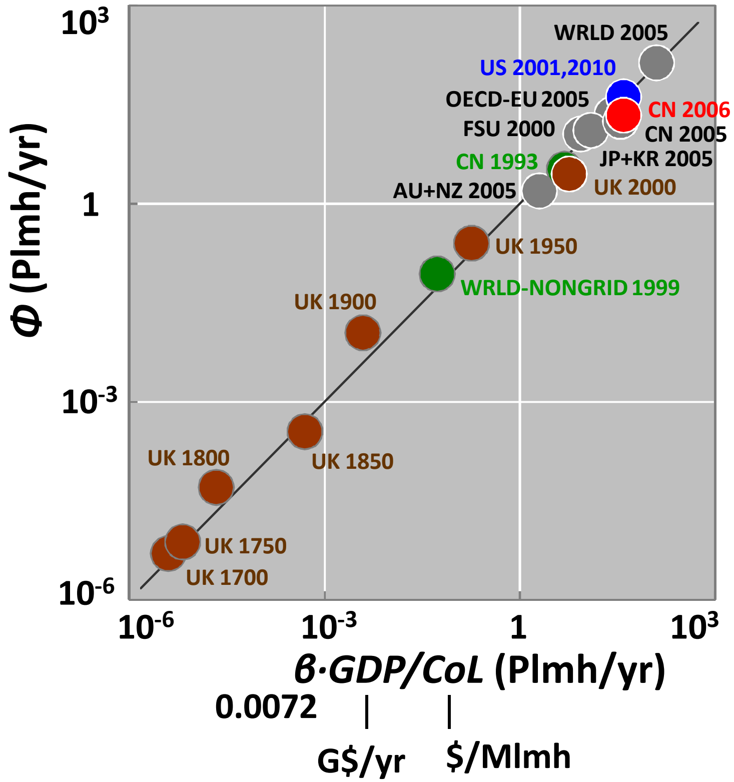
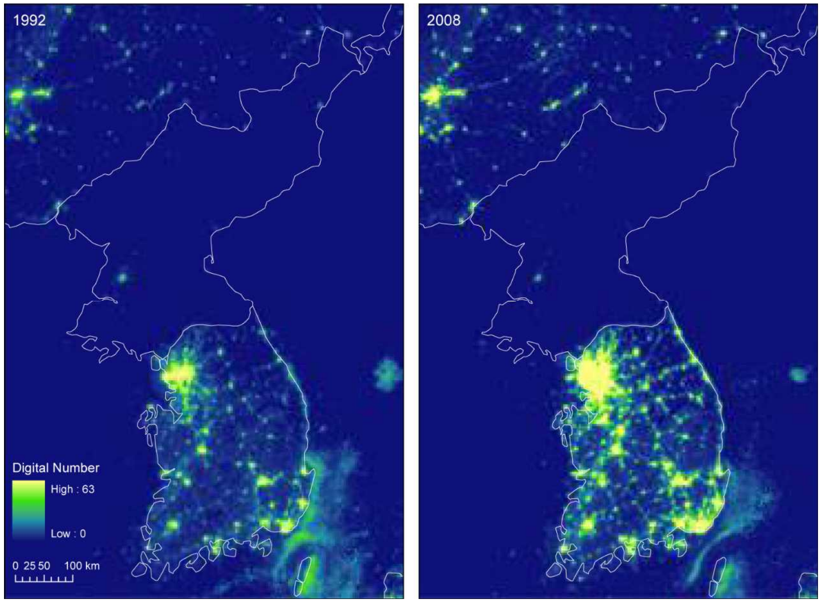


J.Y. Tsao and P. Waide, "The World's Appetite for Light: Empirical Data and Trends Spanning Three Centuries and Six Continents," LEUKOS **6**, 259-281 (2010).



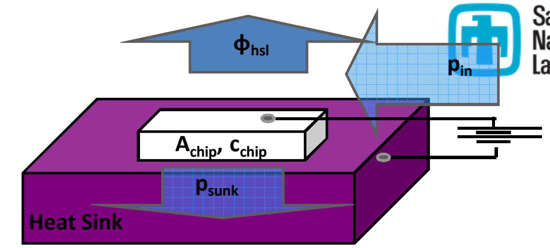
1992 2008

Korean Peninsula

J.V. Henderson, A. Storeygard, and D.N. Weil, "Measuring Economic Growth from Outer Space," Amer. Economic review **102**, 994-1028 (2012).

Ultra-efficient SSL: two approaches

Sandia National Laboratories



4 Heat-sink-limited white light flux

$$\Phi_{hsl} = \frac{MWLER \cdot \varepsilon_B \varepsilon_{PP}}{\left(P_{in}/A_{chip}\right)} \cdot \left[\frac{2\kappa_T \sqrt{4/\pi} \cdot \Delta T_{max}}{(1-\varepsilon_B \varepsilon_{PP}) \cdot}\right]^2$$

3 Heat-sink-limited chip area

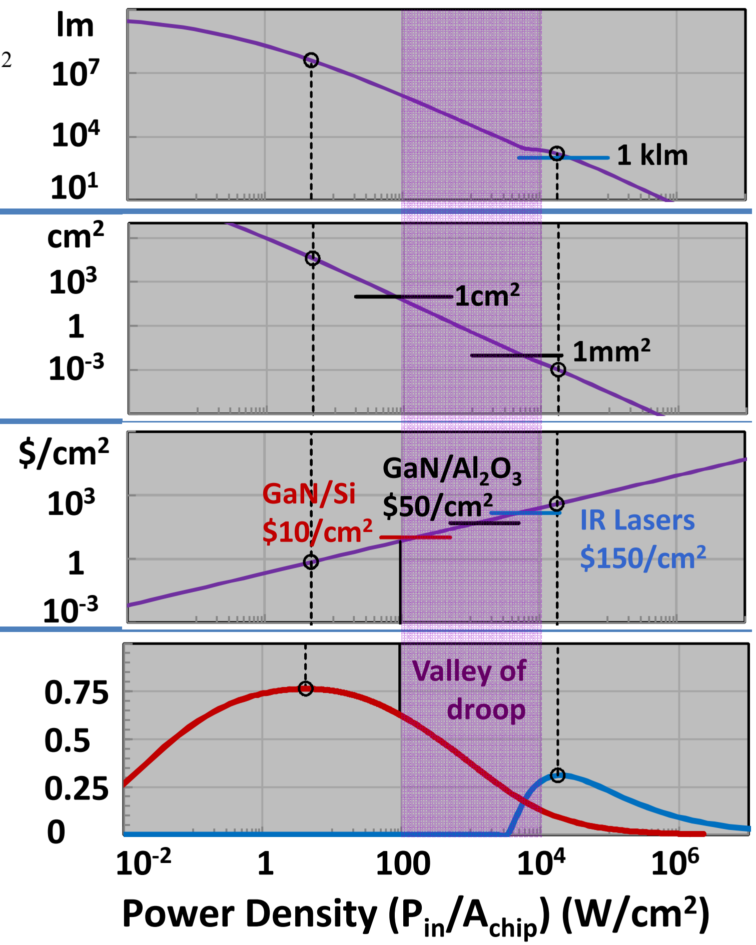
$$A_{hsl} = \left[\frac{2\kappa_T \sqrt{4/\pi} \cdot \Delta T_{max}}{(1-\varepsilon_B \varepsilon_{PP}) \cdot \left(P_{in}/A_{chip}\right)}\right]^2$$

2 Chip areal cost necessary for $CoL_{cap} < CoL_{ope}/6$

$$c_{chip} = \frac{L \cdot CoE}{6\alpha} \cdot \left(P_{in}/A_{chip}\right)$$

1 Efficiency, and its valley of death

$$\varepsilon_B \,(Blue\ Emitter\ Efficiency)$$



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).

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 and could enable novel luminaires.
- Ultra-efficient SSL could lead to cost savings and/or increased productivity.

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.