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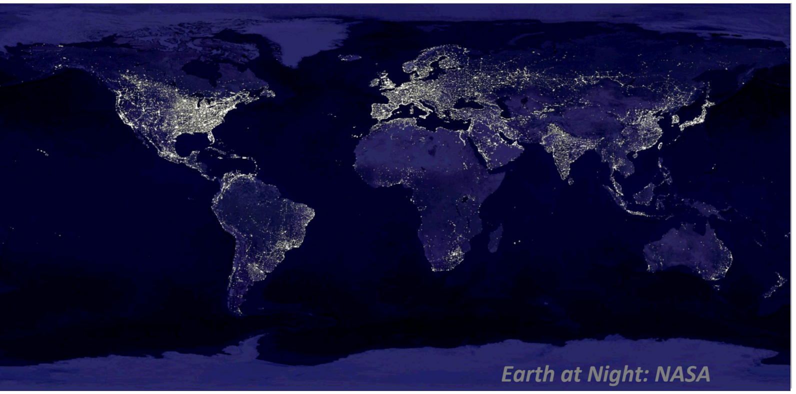
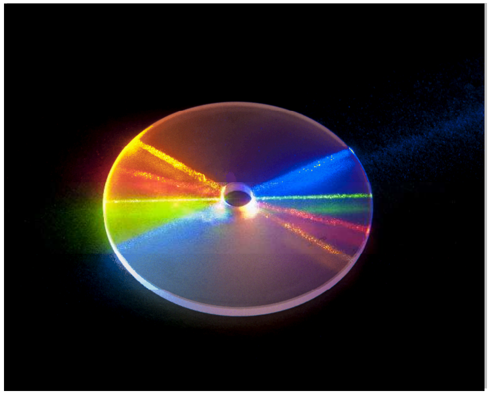
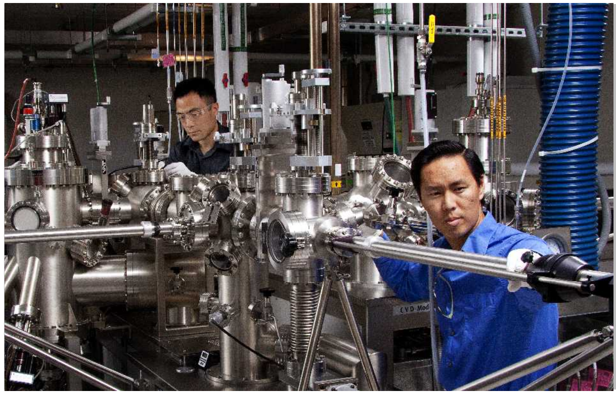
SAND2014-19561PE







Lighting the Future: The Science of Solid-State Lighting

SSLS EFRC

SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

Jeremy B. Wright

U.S. DEPARTMENT OF ENERGY

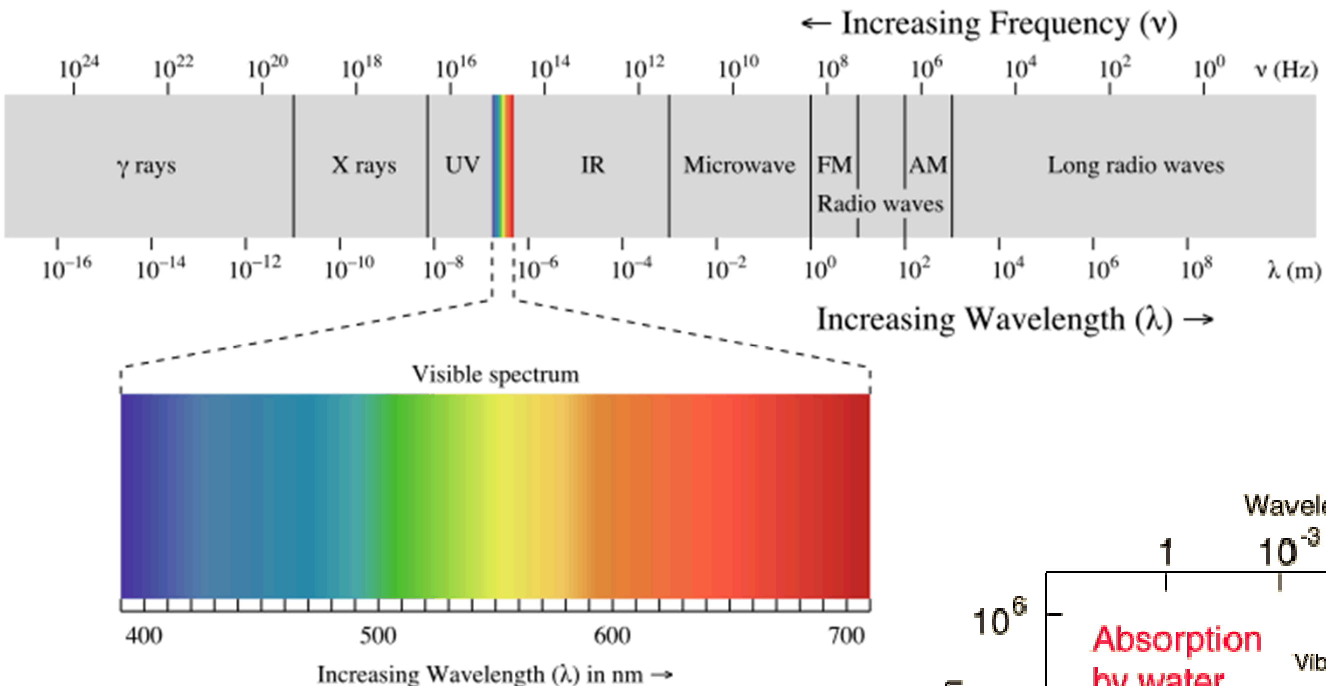
NNSA National Nuclear Security Administration

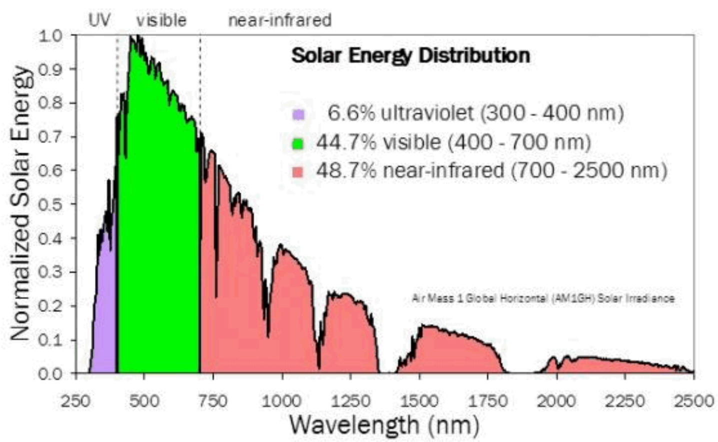
Work at Sandia National Laboratories was supported by Sandia's Solid-State-Lighting Science Energy Frontier Research Center, funded by the U.S. Department of Energy, Office of Basic Energy Sciences. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

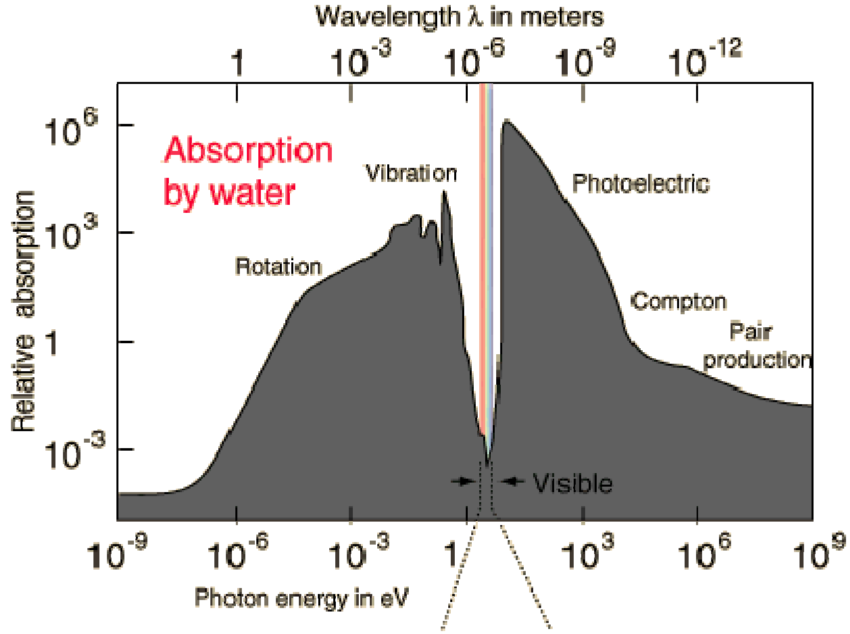
Outline

- Introduction to Solid-State Lighting
- Technology Challenges to be solved
- EFRC for Solid-State Lighting Science at Sandia
- What does the future hold?

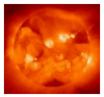
Light, Life and Vision





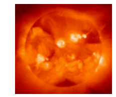


The evolution of vision

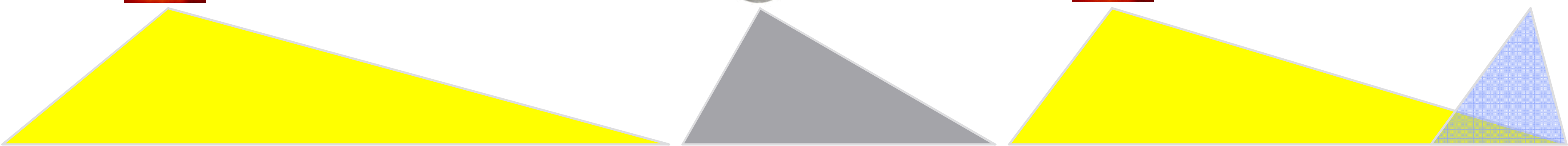


Full-disk view of the X-ray Sun and was produced by the Yohkoh solar observatory in 1991. http://en.wikipedia.org/wiki/File:Yohkohimage.gif

Full moon view from Earth in Belgium, courtesy of Luc Viatour. http://en.wikipedia.org/wiki/File:Full_Moon_Luc_Viatour.jpg



Bridgelux Helieon Solid-State Lamp. http://www.bridgelux.com/products/helieon.html



Asaphus species (Trilobite) picture taken by DanielCD. http://en.wikipedia.org/wiki/File:Asaphus_species_trilobite.jpg

Red Lory (Eos bornea) upper body preening feathers. http://en.wikipedia.org/wiki/File:Red_Lory_%28Eos_bornea%29-6.jpg

Gray wolf, canis lupus, courtesy of Chris Muiden. http://en.wikipedia.org/wiki/File:Canis_lupus_265b.jpg

Olive baboon in Kenya; courtesy of Ryan Harvey; http://en.wikipedia.org/wiki/File:Male_Olive_Baboon_2.jpg

A baby wearing many items of winter clothing: headband, cap, fur-lined coat, shawl and sweater. Courtesy of Andrew Vargas, Clovis, United States. http://en.wikipedia.org/wiki/File:Well-clothed_baby.jpg

Mantis Shrimp: 16 different photoreceptor pigments, 12 for color sensitivity, others for color filtering, polarization, etc

200 Years of Lighting Technology

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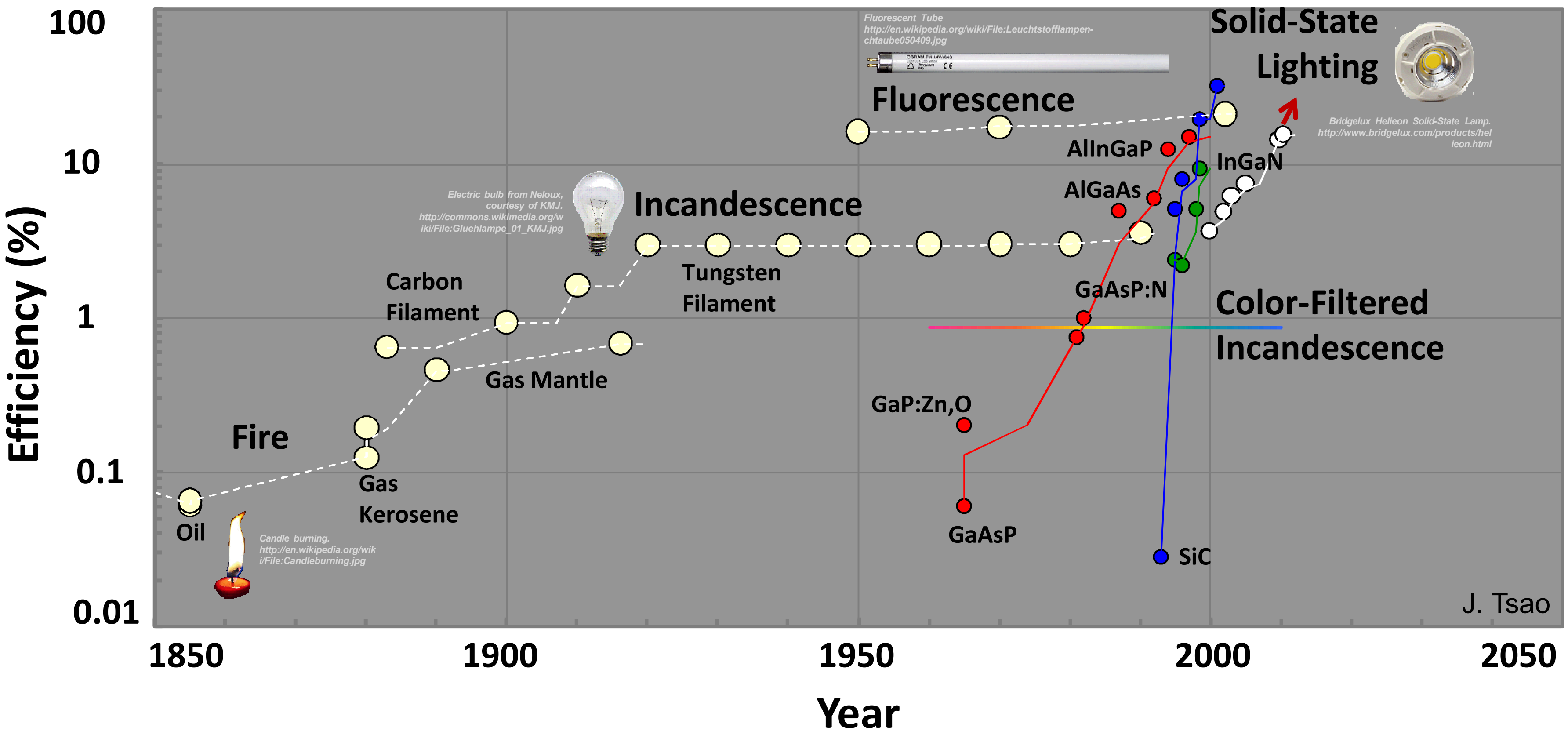

Why Solid-State Lighting Matters

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- ~22% of electricity consumption is used for lighting
- Lighting is one of the most ***inefficient*** energy technologies in buildings
- 2012 DOE projections:
  - 36% adoption by 2020
  - 74% adoption by 2030
  - decrease electrical use from lighting by ~46%

Projected Year 2030 Savings	US
Electricity used (TW-hr)	300/year
$ spent on Electricity	$30B/year
Electricity generating capacity (GW)	50
Carbon emissions (Mtons/year)	210

Efficiencies of energy technologies in buildings:

Heating: 70 - 80%
Elect. motors: 85 - 95%
Fluorescent: ~25%
Incandescent: ~ 5%

US DOE target: 50%
"Ultra-efficient" SSL: ≥ 70%

Smart, ultra-efficient SSL: is it worth pursuing?

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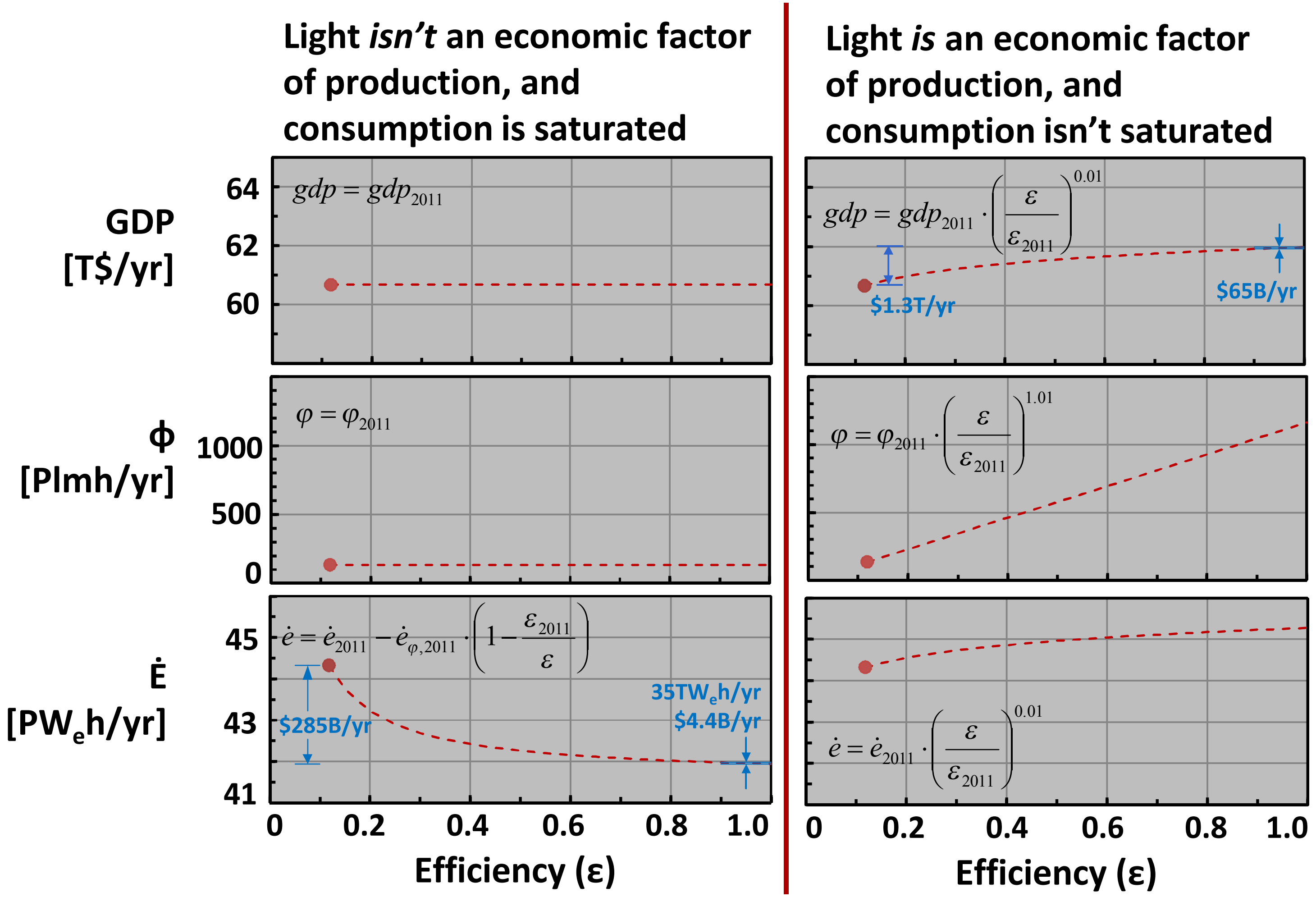
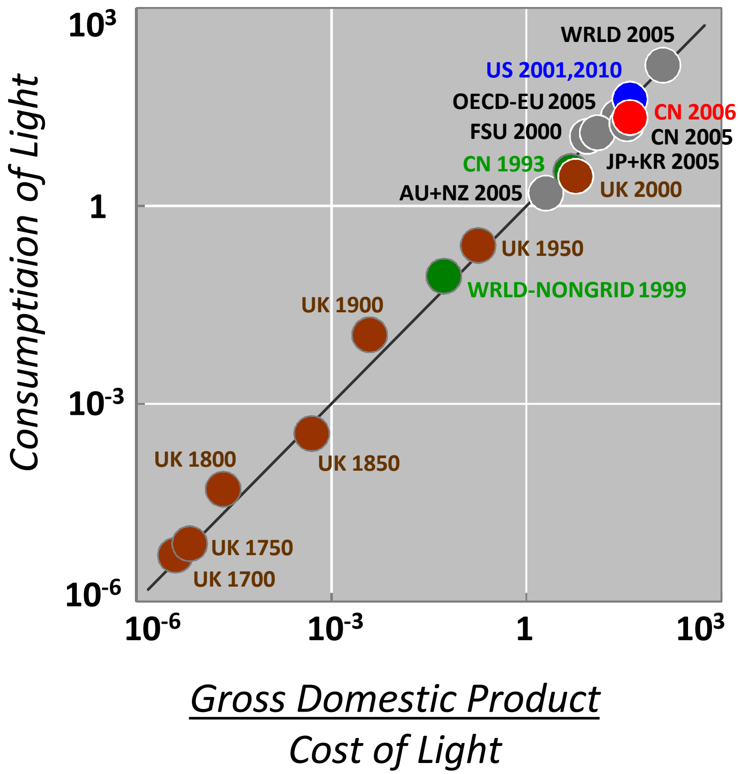
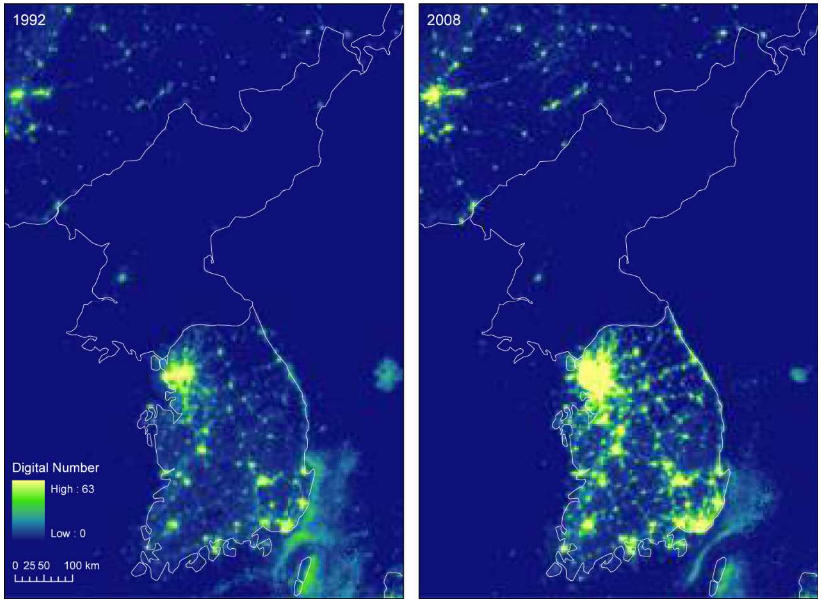


J.Y. Tsao, H.D. Saunders, J.R. Creighton, M.E. Coltrin and J.A. Simmons, "Solid-state lighting: an energy-economics perspective," J. Physics D **43**, 354001 (2010).

Lighting Leads to Increased Productivity





1992 2008

Korean Peninsula

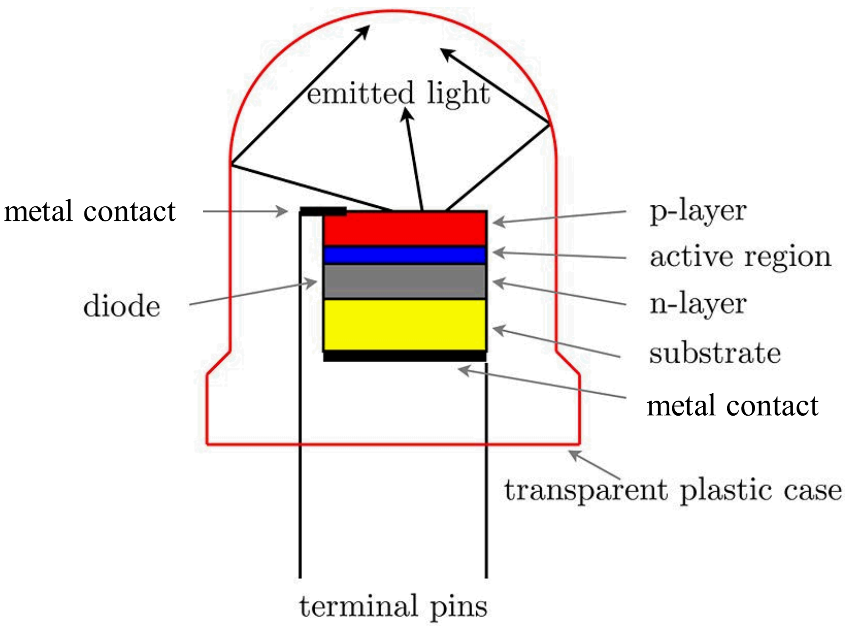
GDP ↑, Consumption ↑
Cost ↓, Consumption ↑

The more efficiently light is produced the more we consume and the more productive we are

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).

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

How Light Emitting Diodes Work



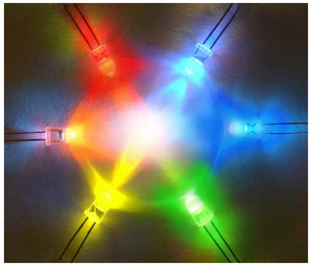
- An LED is a semiconductor device, i.e., p-n (positive-negative) junction
- Current flows from the p-side to n-side
- Electrons and holes (“charge carriers) flow into the junction from either side
- When an electron meets a hole, energy is released as <u>light</u>
- Semiconductor material composition determines color of emitted light

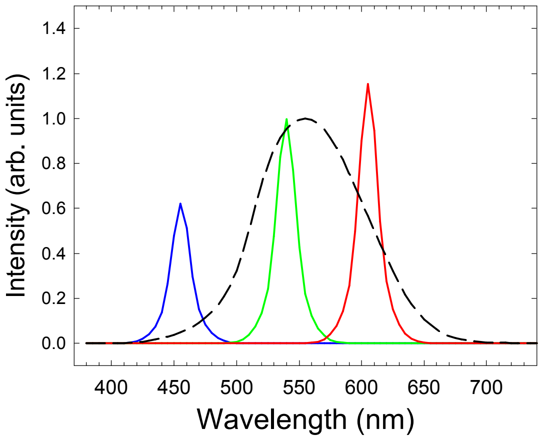
http://commons.wikimedia.org/wiki/File:LED_Device.jpg

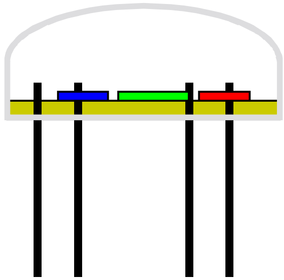
Two Approaches for White Light

Multi-LED:

Mix light from multiple LEDs



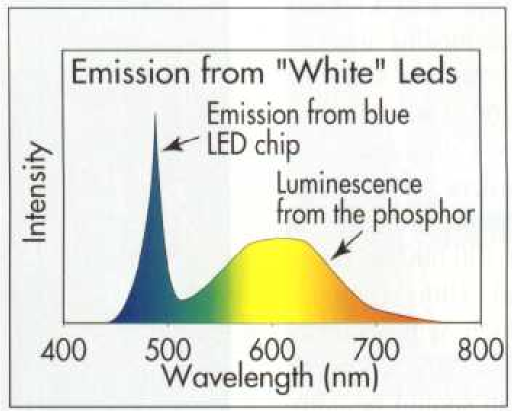


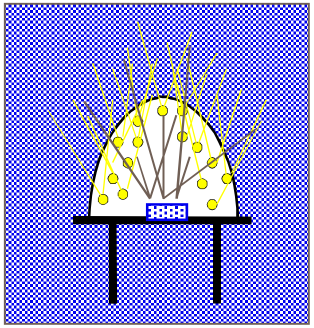


High Control
High Efficiency
High Cost

LED + Phosphors:

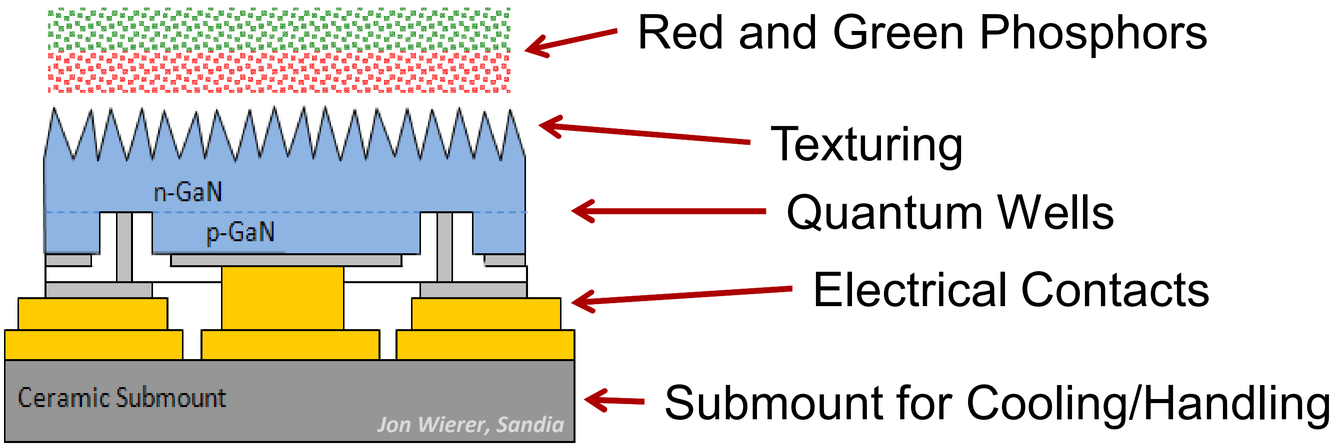
Use blue or near-UV LED to pump a mixture of phosphors



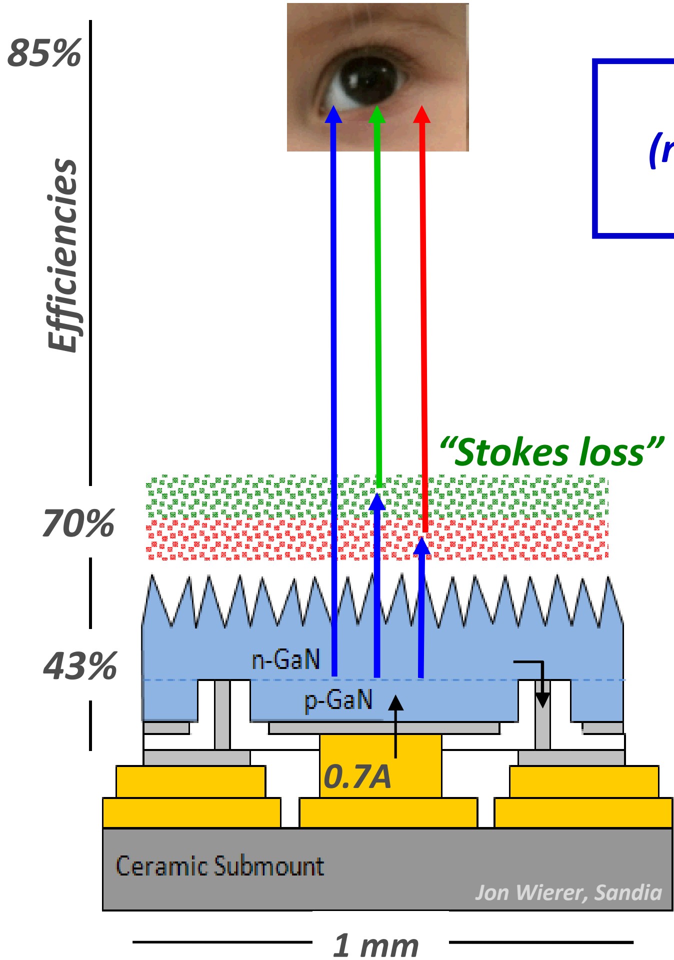


Lower Control
Lower Efficiency
Lower Cost

Parts of a "White" Phosphor LEDs



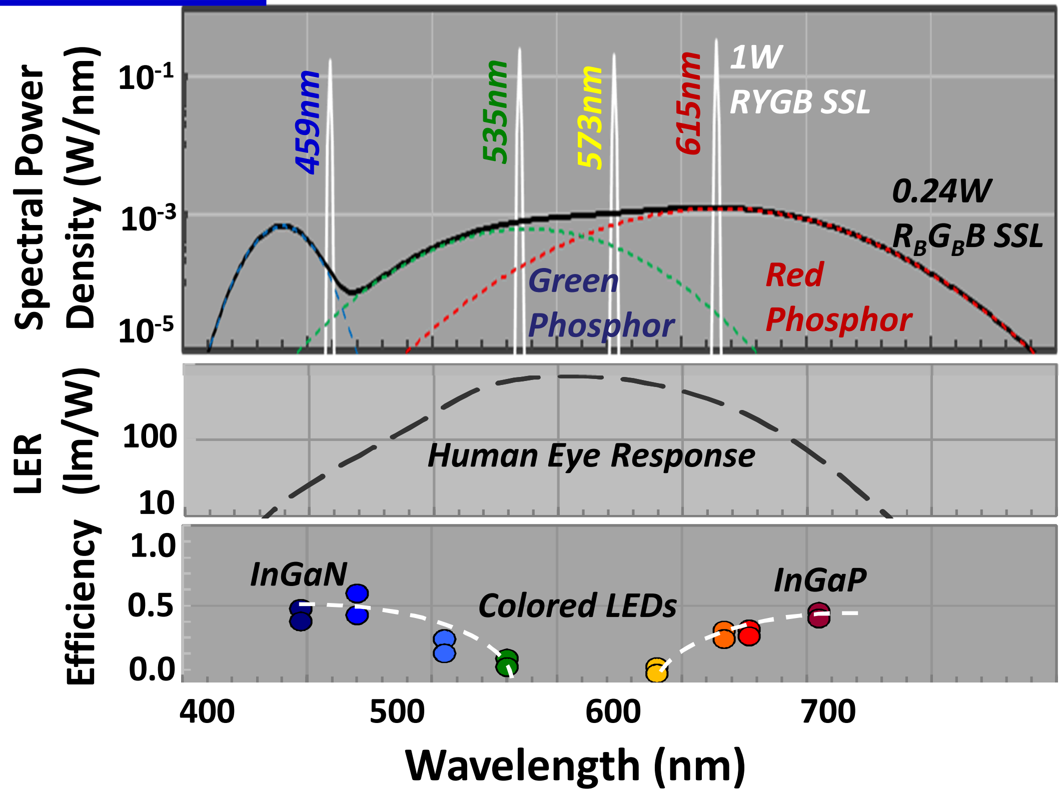
Limits to Efficiency



1. Efficiency Droop (near-100% efficiency at all currents)

2. Green-Yellow Gap (near-100% efficiency at all wavelengths)

3. Narrow-linewidth λ downconversion (esp. red)



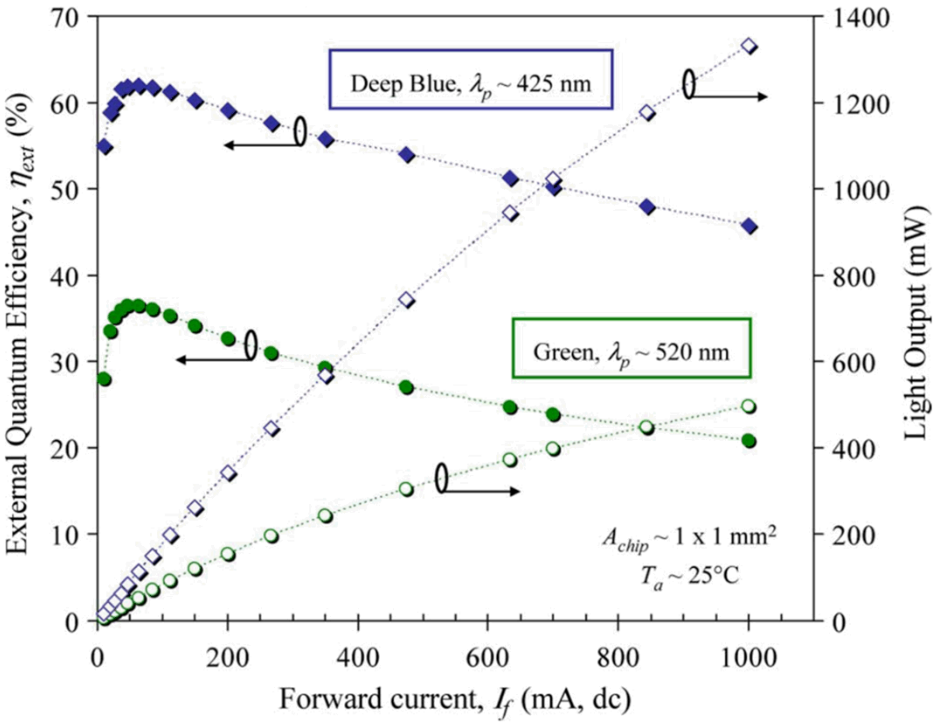
Competition between Radiative and Nonradiative processes determines LED efficiency

$$\varepsilon_{IQE} = \frac{Bn^2}{An + Bn^2 + Cn^3 + Dn^m + \ldots}$$

- An: **Shockley-Read-Hall (nonradiative at defects)**
- Bn^2: **Radiative**
- $Cn^3 + Dn^m$: **Auger and higher order processes**

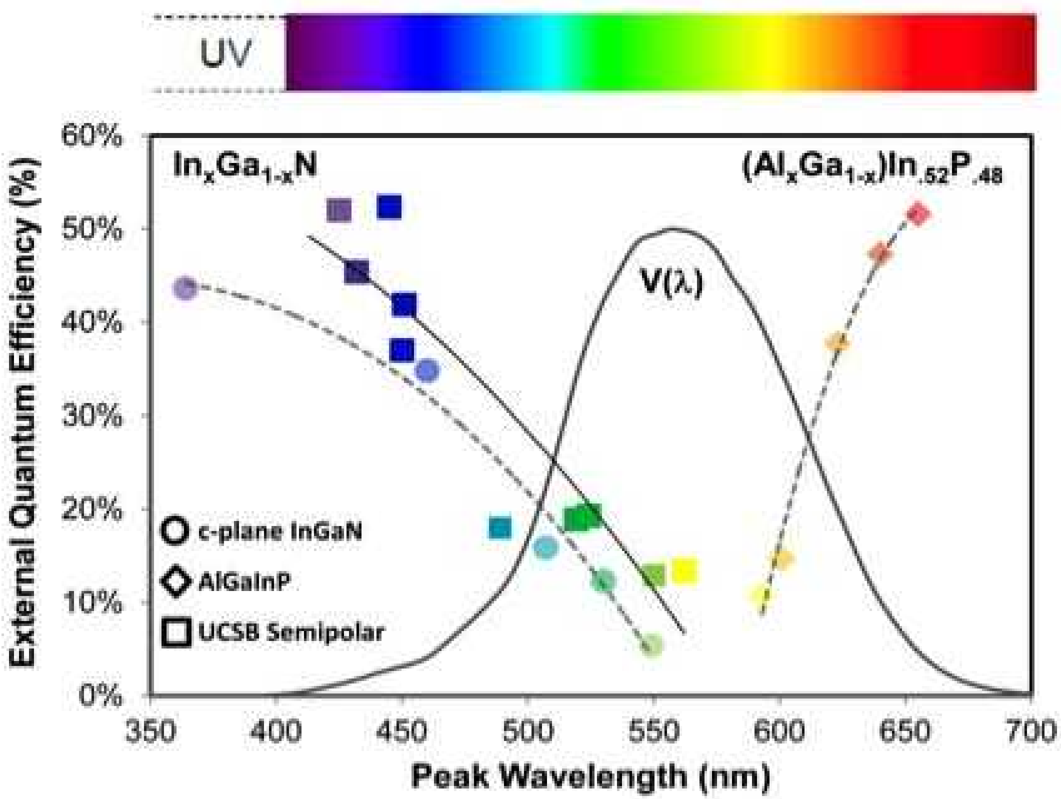
"*Internal Quantum Efficiency*" (IQE) depends on the charge-carrier density, $\boldsymbol{n}$

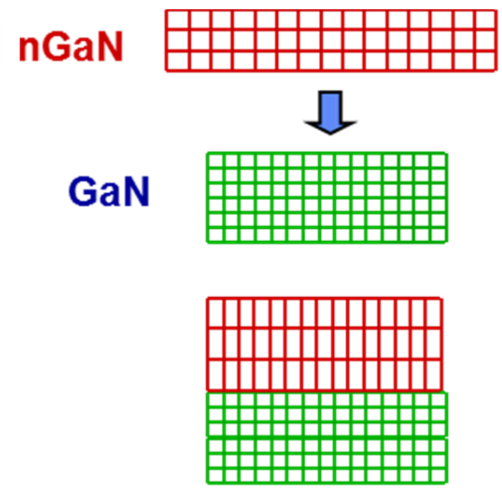
LED "Efficiency Droop" at High Currents



- Efficiency peaks at low current (35 mA/mm^2)
- Commercial SSL ~700 mA/mm^2
  - 2,000 mA/mm^2 (desired)
- Intense R & D (industry and academia)
- Mechanism still under debate
  - Auger recombination
  - Carrier transport
  - Internal electric fields

LED efficiency drops as Indium content is increased ("Green Gap")

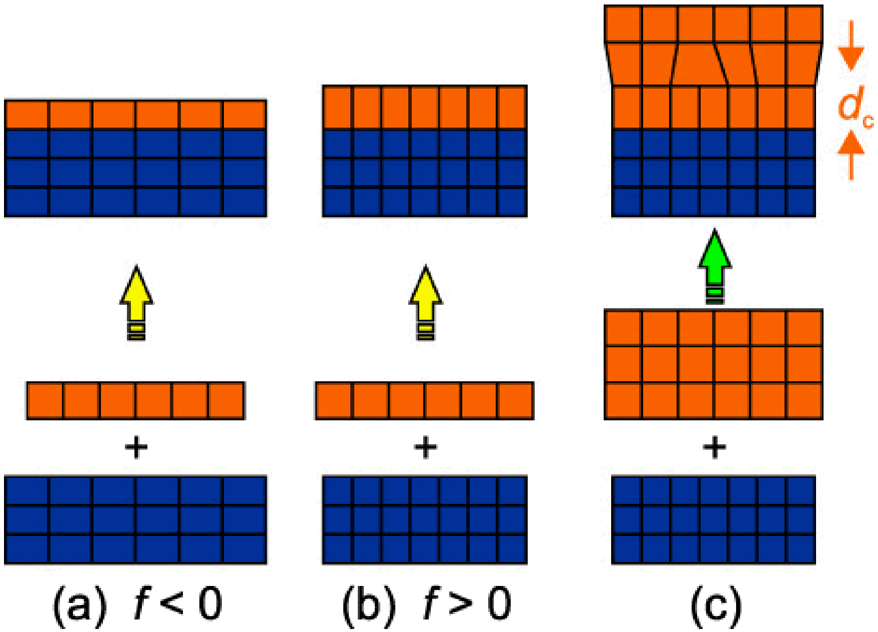




Compressively strained InGaN on GaN

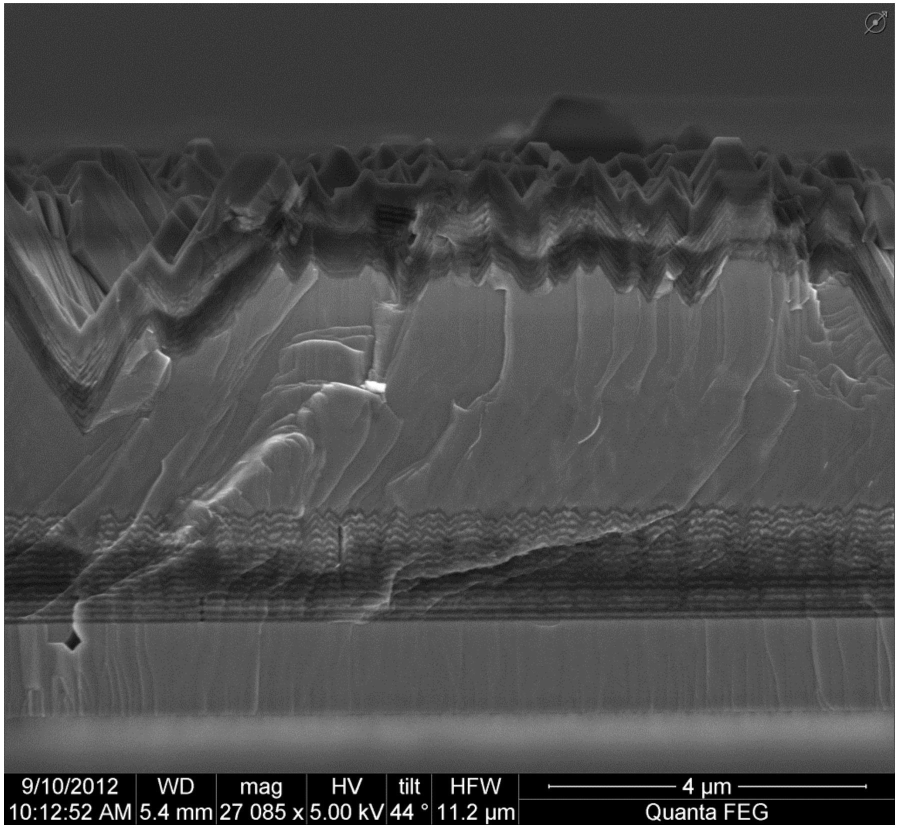
A Closer Look at III-Nitride Semiconductors: Defects!

What happens when 2 crystals don't have the same lattice constant and we try to grow one on top of the other

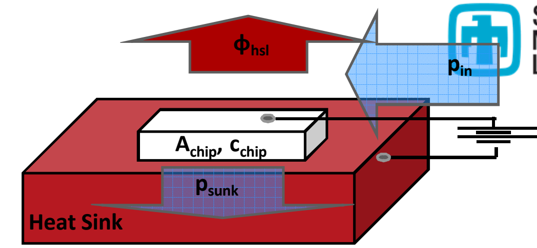


(iopscience.org)

Electron Micrograph (cross section)



Ultra-efficient SSL: two approaches



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

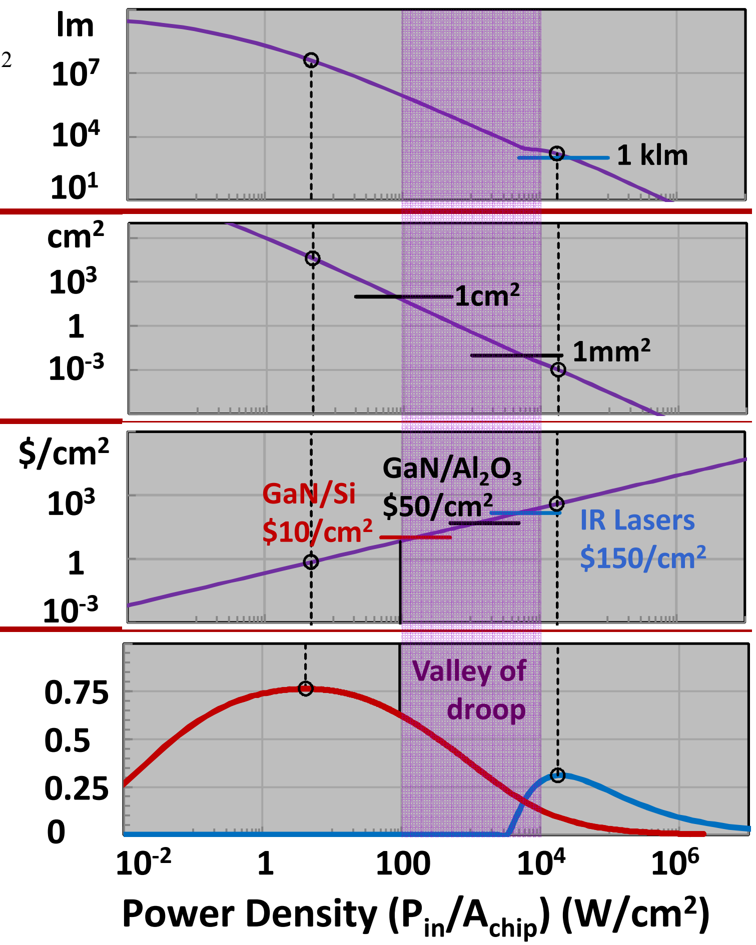
$$A_{hsl} = \left[\frac{2\kappa_T \sqrt{4/\pi} \cdot \Delta T_{max}}{(1-\varepsilon_B \varepsilon_{PP}) \cdot \left(P_{in}/A_{chip}\right)}\right]^2$$

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

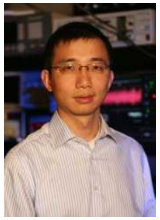
$$\varepsilon_B \, (Blue\ Emitter\ Efficiency)$$



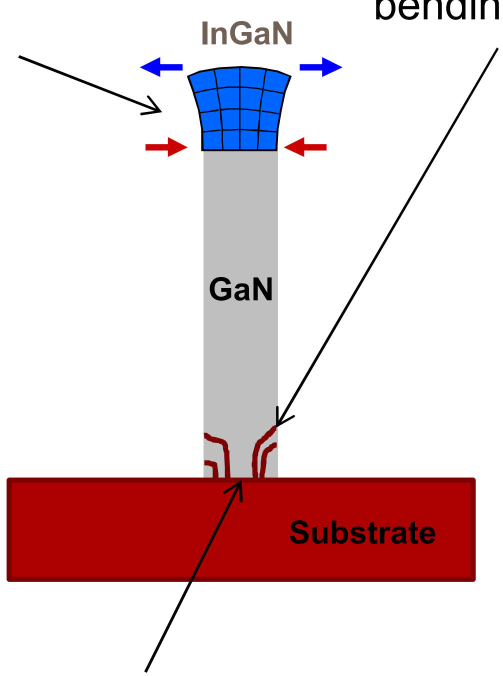
J.J. Wierer, J.Y. Tsao, D.S. Sizov, "Comparison between blue lasers and light-emitting diodes for future solid-state lighting," Laser & Photonics Reviews (2013).

SSLS EFRC team

For more information, visit:
http://ssls.sandia.gov

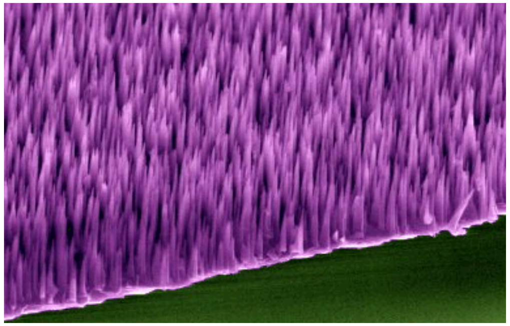


Why Nanowires Are a Good Idea

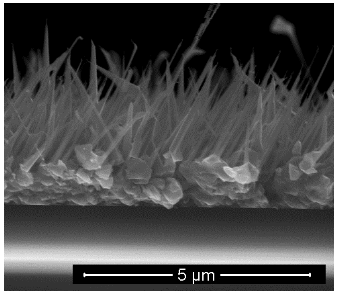


Nanowires

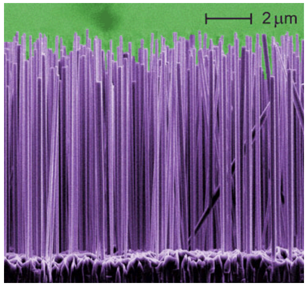
Nanowires can be grown ("bottom up"):



GaN NWs Sandia

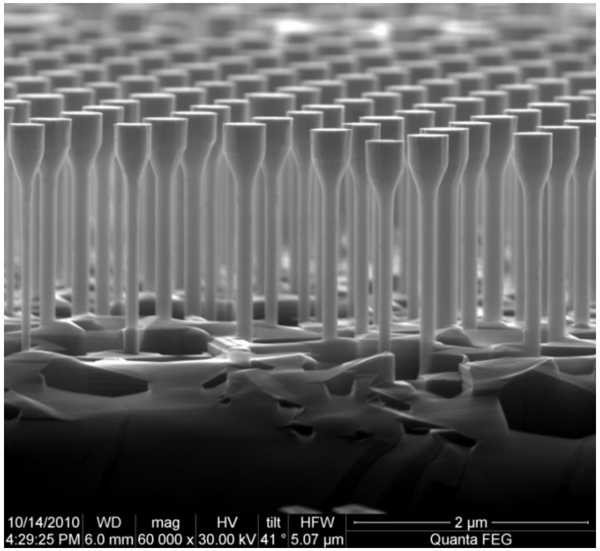


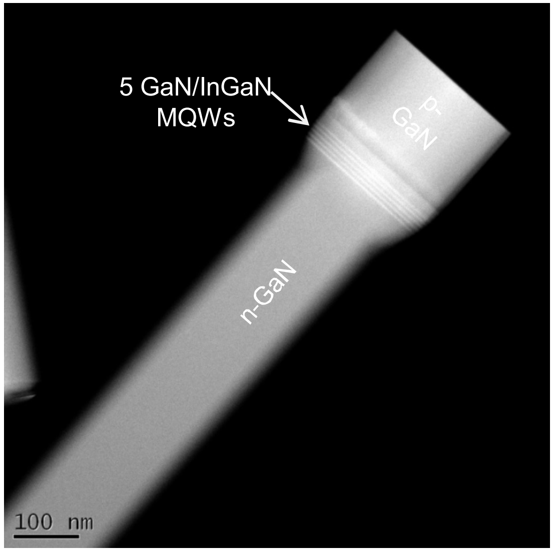
GaN NWs on tungsten foil - Sandia



GaN NWs on Si - NIST

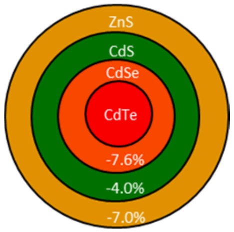
Nanowires can be fabricated ("top down):

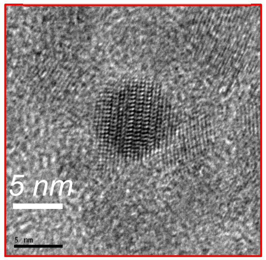




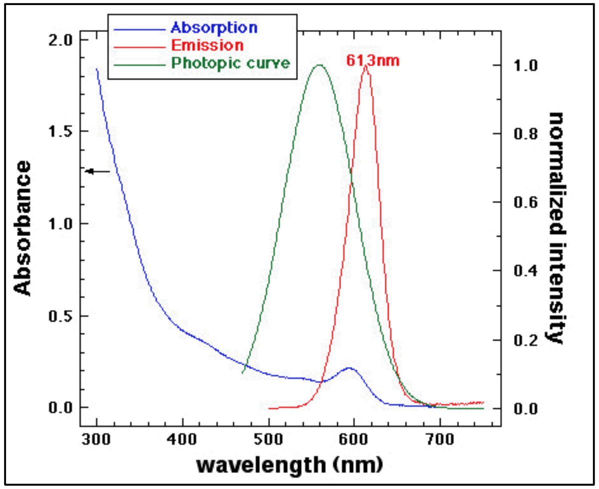
"nano LED"

Narrow linewidth red quantum dot emitters for solid-state lighting



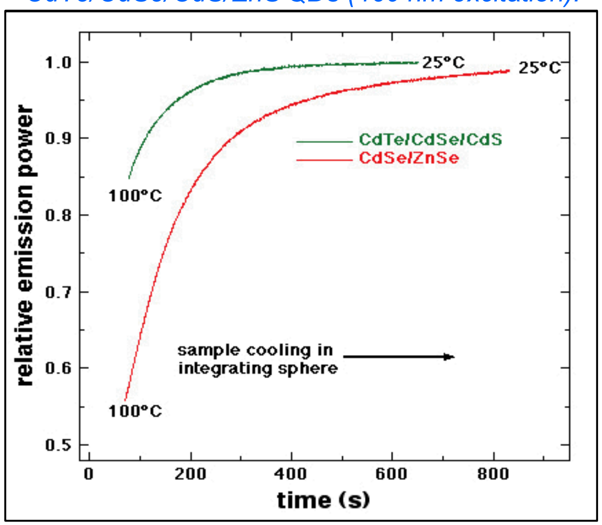


TEM image of CdTe core coated with 10 CdSe shells.



Absorbance and photoluminescence emission of CdTe/CdSe/CdS/ZnS QDs (460 nm excitation).

Emitted light power from QDs as they are cooled from 100ºC to room temperature.

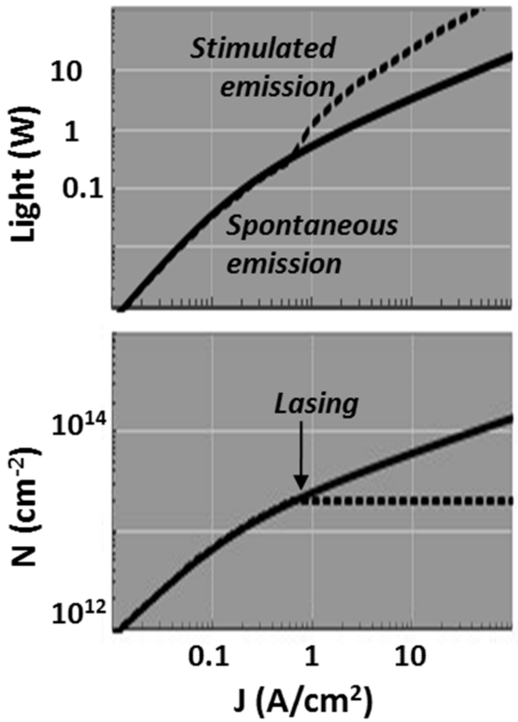


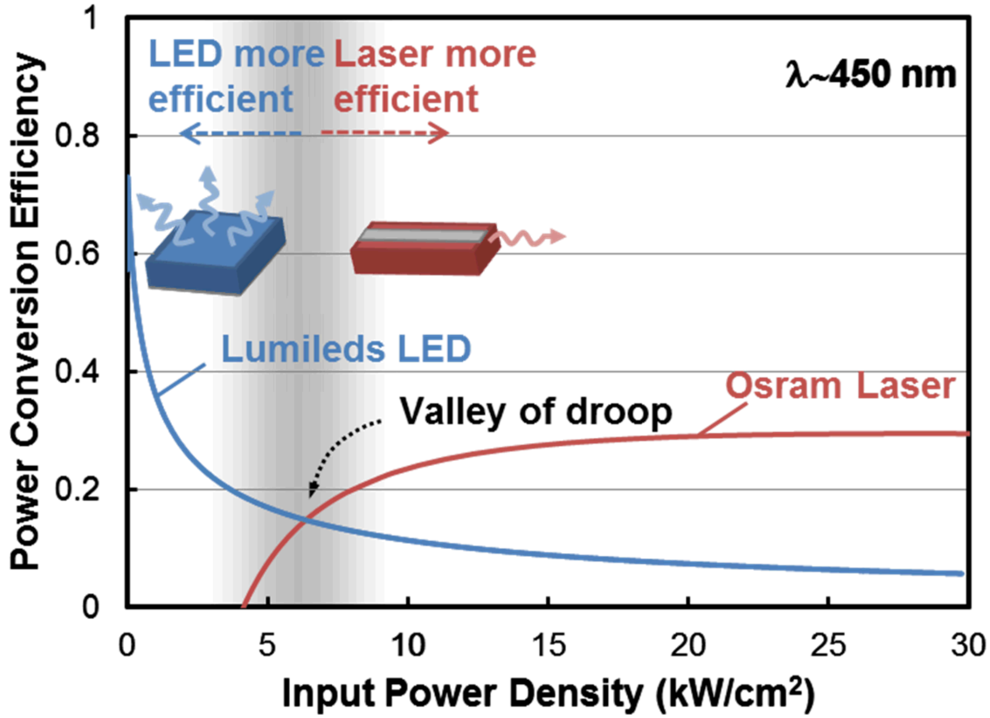
Emission centered at 613 nm, ideal for SSL applications

Core / Shell / Shell QD structure shows much less efficiency-quenching at SSL operating temp.

L.E. Shea-Rohwer, J.E. Martin, X. Cai, D.F. Kelley, ECS J. Solid State Science & Technology, 2 [2], R3112-R3118 (2013)

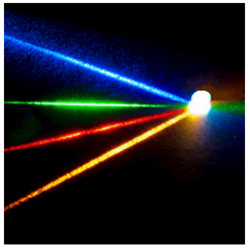
Could lasers be part of the solution?



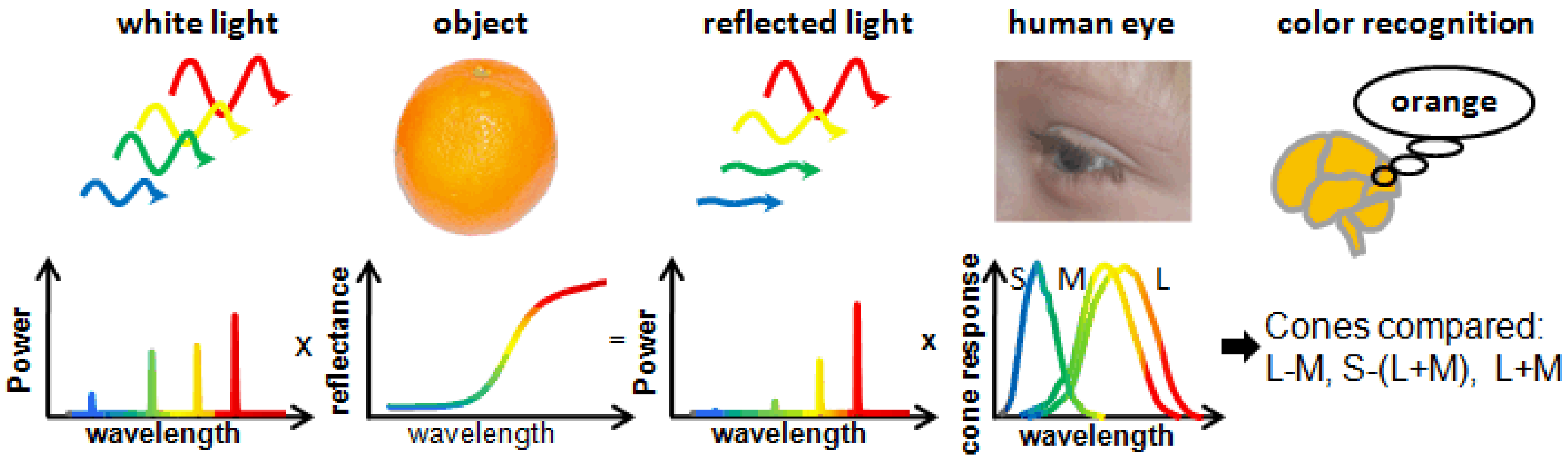


- **After threshold lasers are not affected by efficiency droop**
- **Lasers are more efficient at higher input power densities**
- **Research needed to lower threshold / improve efficiency**
  - **InGaN materials; device designs (nano???)**

Could I use Lasers to Create White Light? ("Spikey" White Spectrum)



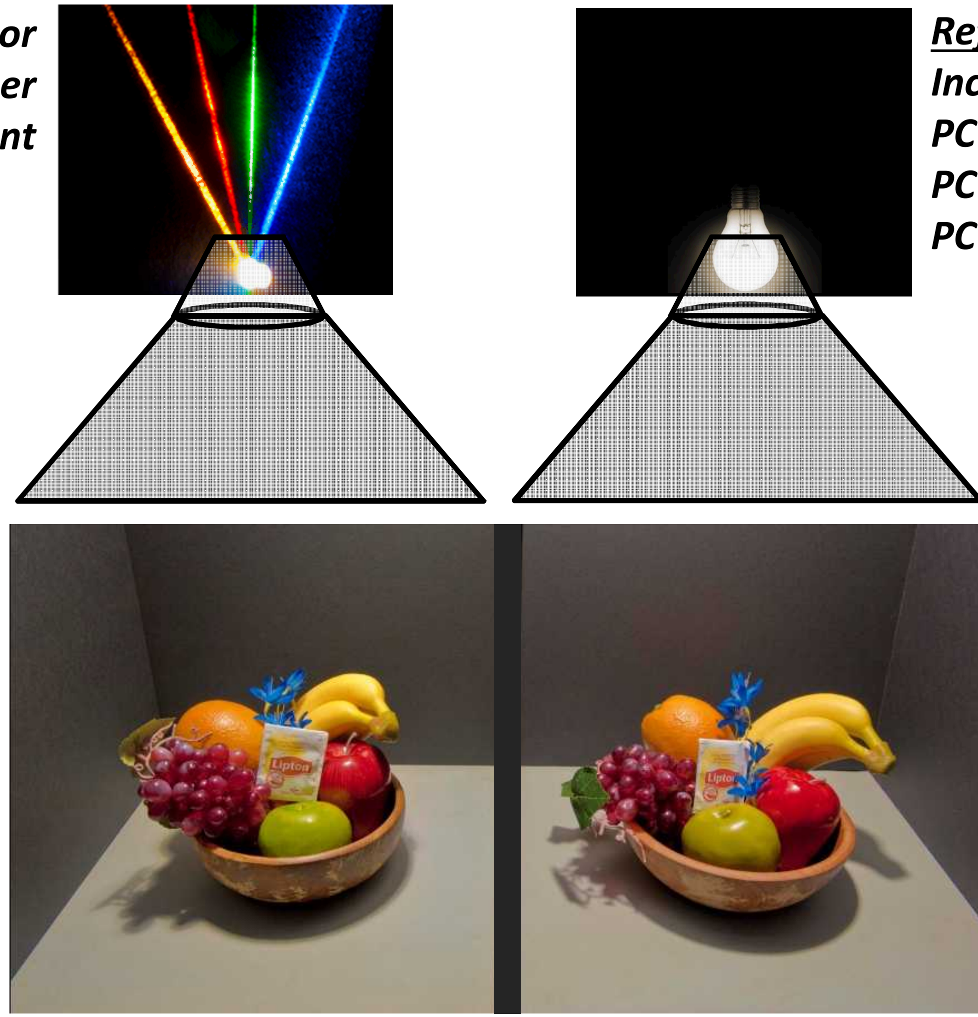
Among other things, lasers produce very narrow spectra



Narrow line-width sources (e.g., lasers) can have excellent color rendering

4-Color Laser Illuminant

<u>Reference sources</u>
Incandescent
PC SSL Warm
PC SSL Neutral
PC SSL Cool

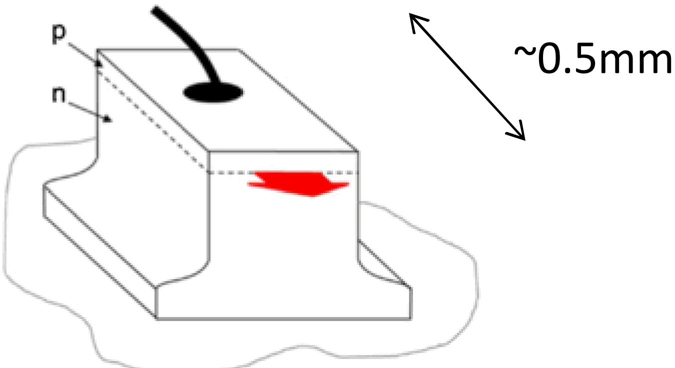


A. Neumann, et al., "Four-color laser white illuminant demonstrating high color-rendering quality," Optics Express **19**, A982-A990 (2011).

Shrinking Semiconductor Lasers….

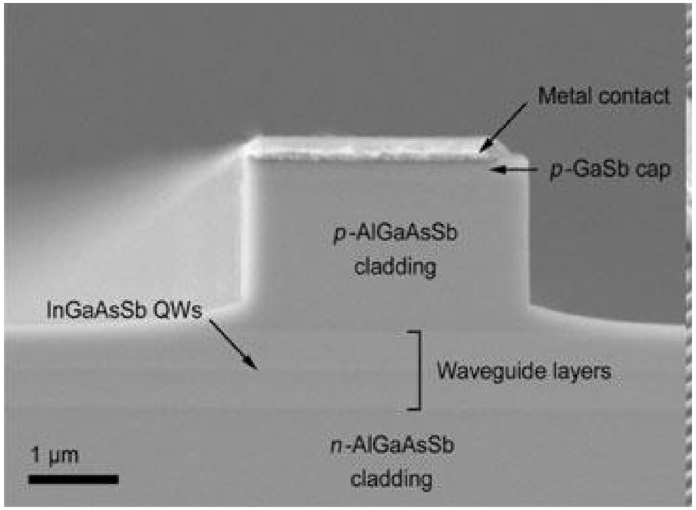
In semiconductor lasers,

- the gain media is similar to an LED
- The mirrors are the cleaved facets



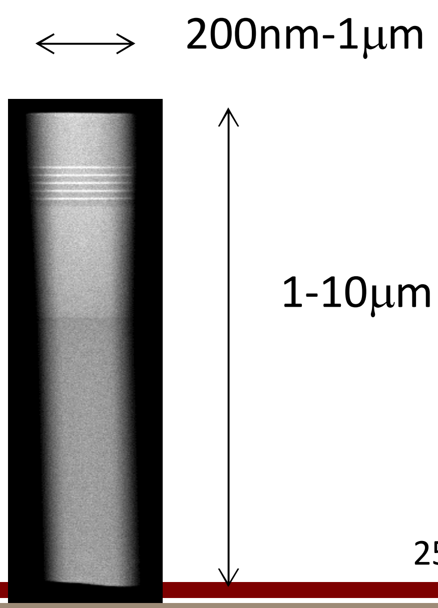
http://m.iopscience.iop.org/0268-1242/27/9/090207/article

This is how a "regular" semiconductor laser looks like



http://www.theiet.org/resources/journals/eletters/4924/lighter-lights.cfm

A "nanowire" laser is much smaller!

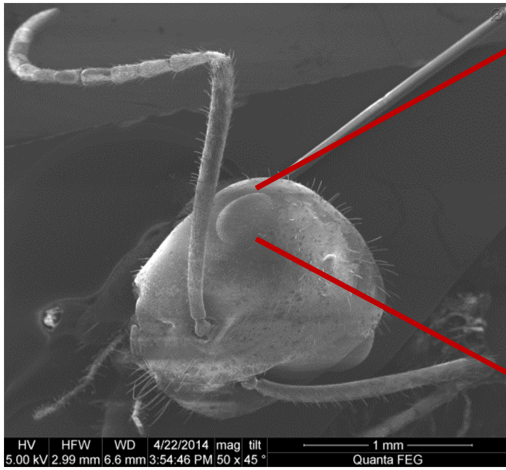


How Small are These Nanowires?

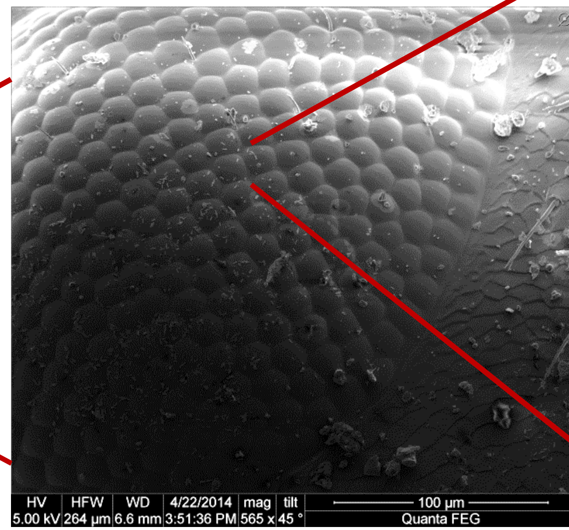
Sandia National Laboratories

(a few μm) long

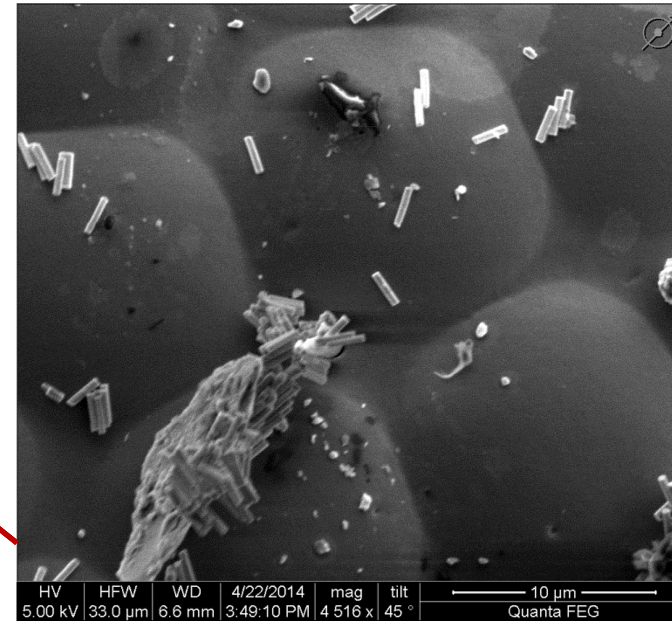
An ant



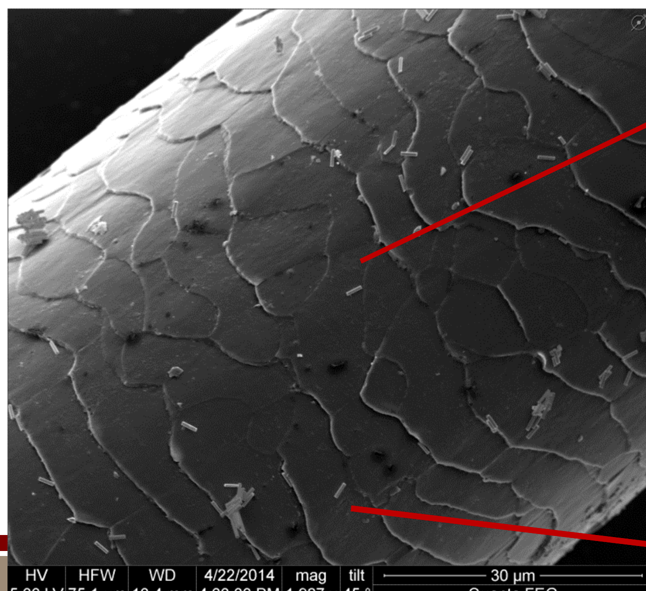
The eye of the ant

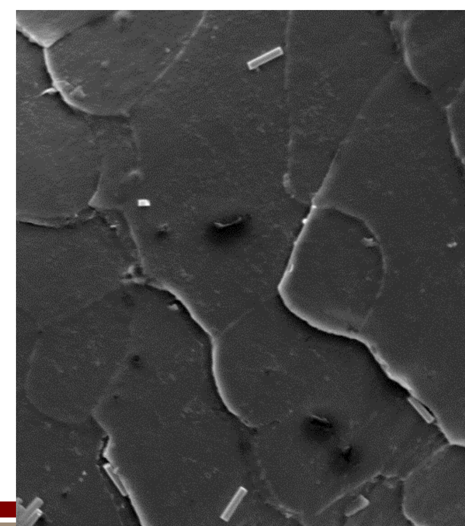


The lenslets of the eye



A hair from a student

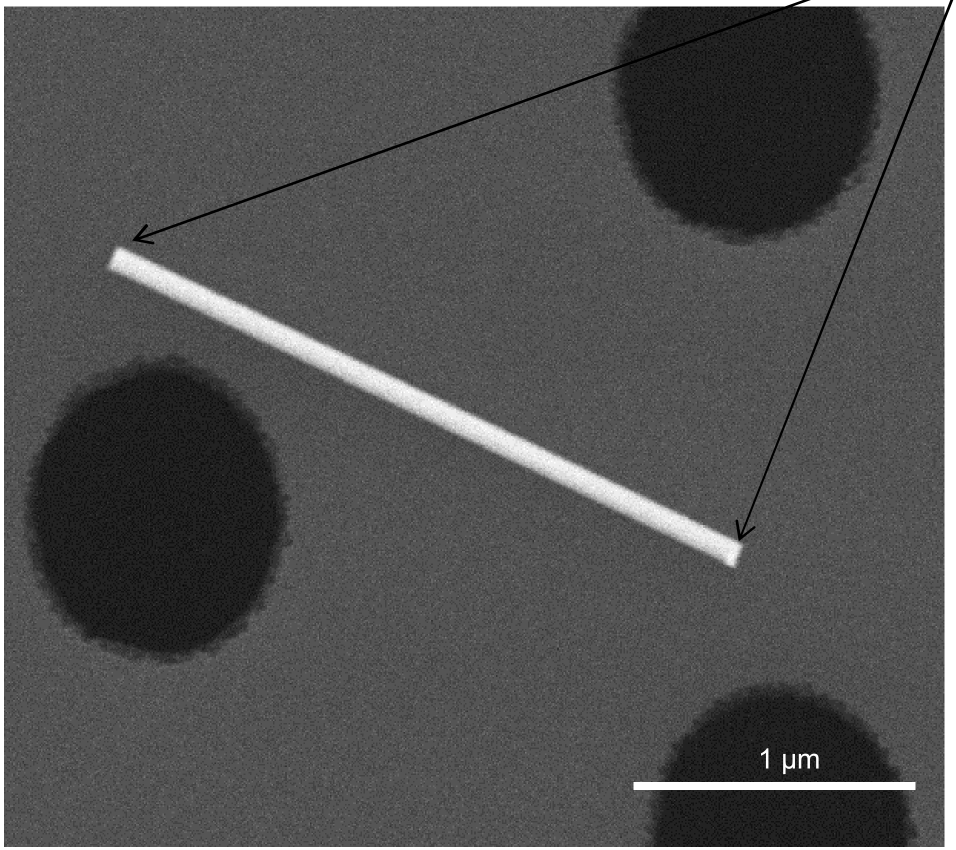


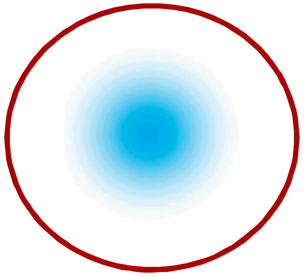


Courtesy of Jeremy Wright, Sandia

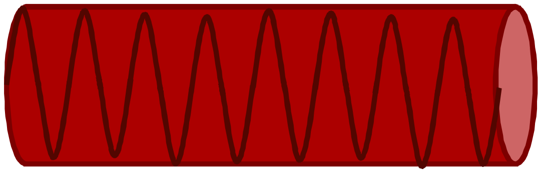
Nanowire Lasers

Two end-facets act as the mirrors

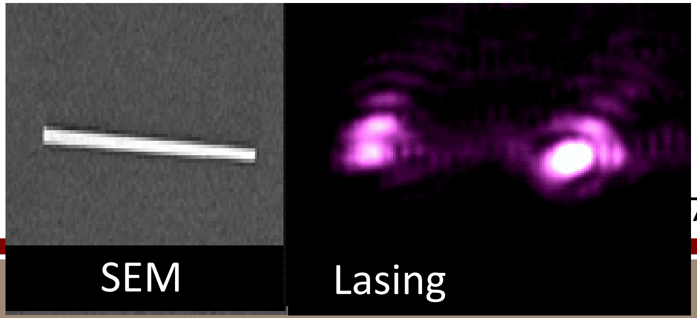




Light is confined in the cross-section



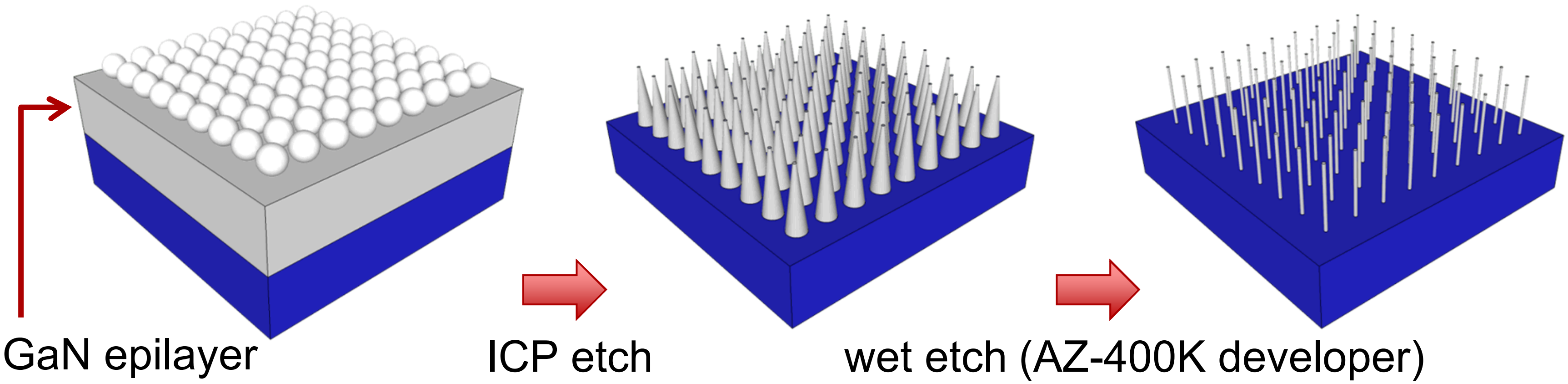
Light oscillates along the length of the nanowire

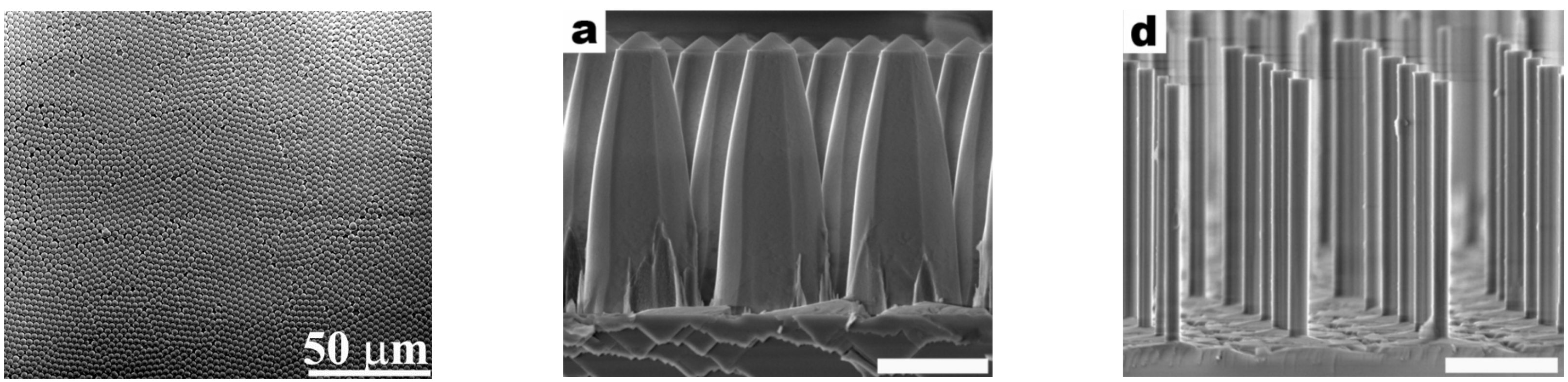


SEM

Advanced Nanowire Fabrication Technique

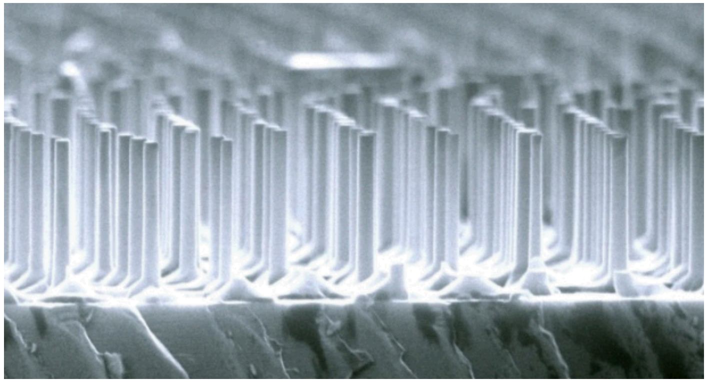
Two-step top-down etch = dry etch + wet etch



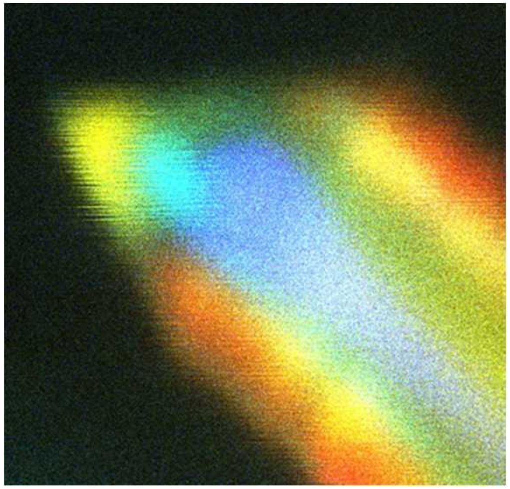


Q. Li, et al. Opt. Express 20, 17873 (2012)

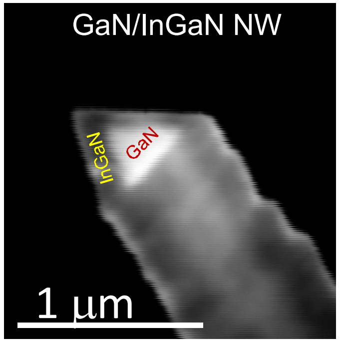
Radial InGaN/GaN nanowires show promise for addressing the green-yellow-red gap



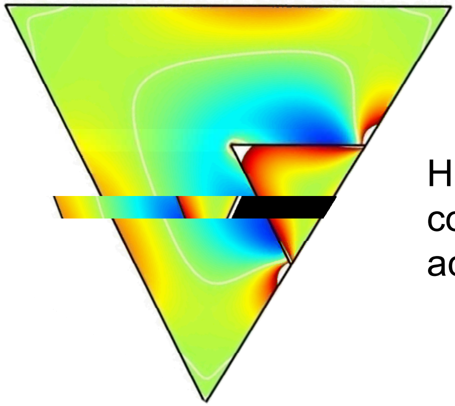
Array of nanowires with controlled height, diameter, and spacing (height ~3 μm; diam. ~100 nm)



Emission out to the red portion of the spectrum (high In content)



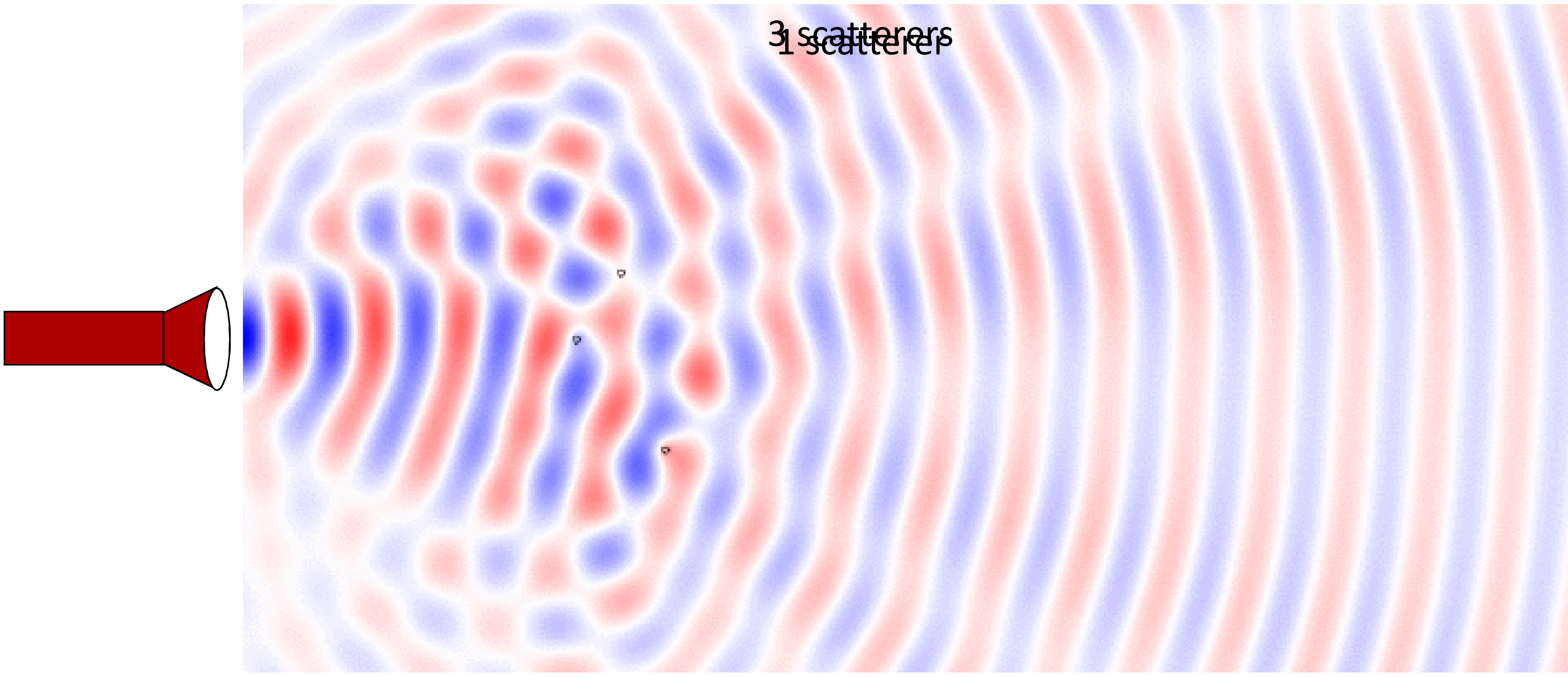
1-D geometry can accommodate lattice-mismatch strain



Highest In-content at corners, which can accommodate strain

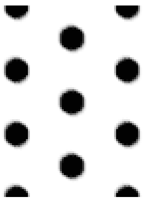
Photonic Crystals

Photonic crystals affect the motion of light by multiple scatterings.
A scatterer disturbs the propagation of electromagnetic radiation.

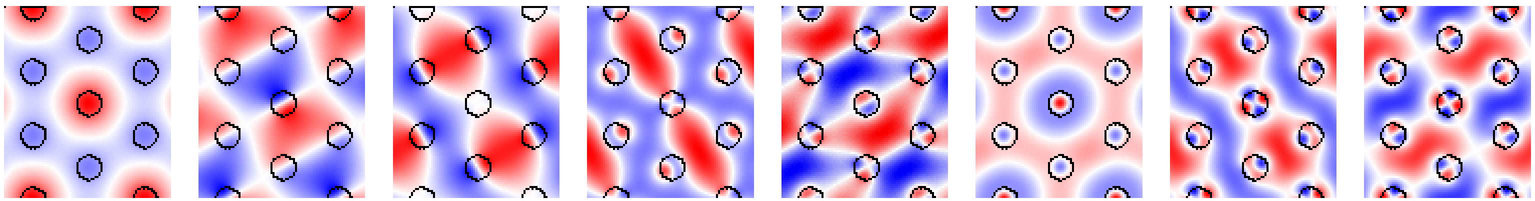


(Steven Johnson, MIT)

Photonic Crystals



A periodic arrangment of pillars, called a lattice causes the light to interfere in different ways depending on the wavelength.

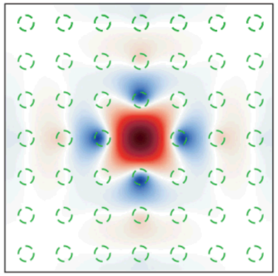


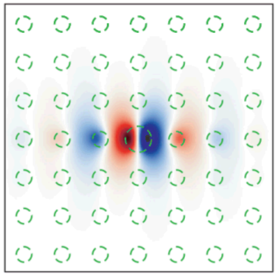
(MPB MIT)

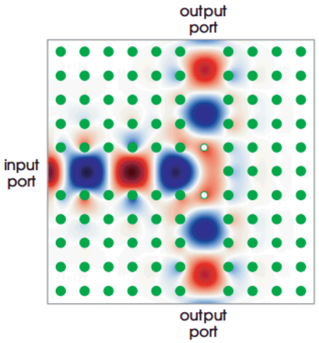
Each interference pattern is called a mode.

Photonic crystals can be used to:

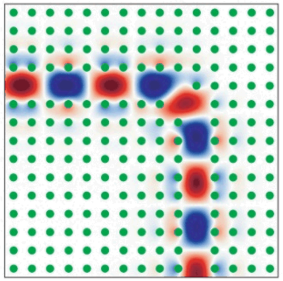
Store Energy







Guide and
bend light



J. D. Joannopoulos, Photonic crystals : molding the flow of light / John D. Joannopoulos ... [et al.]. Princeton : Princeton University Press, c2008.

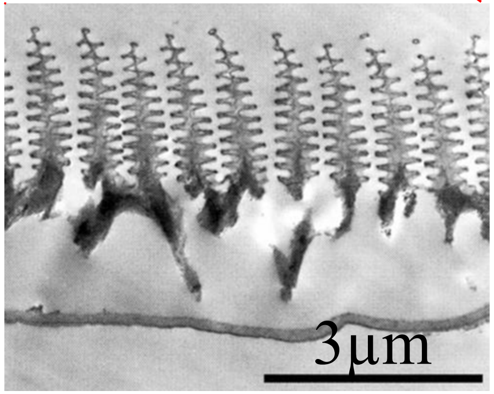
Photonic Crystals Are Everywhere

Morpho rhetenor butterfly

wing scale:

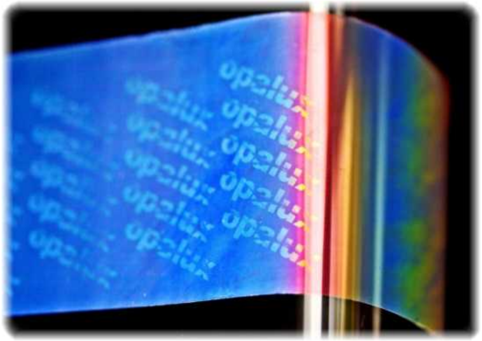
[P. Vukosic *et al.*, *Proc. Roy. Soc: Bio. Sci.* 266, 1403 (1999)]

(Courtesy S. Johnson, MIT)

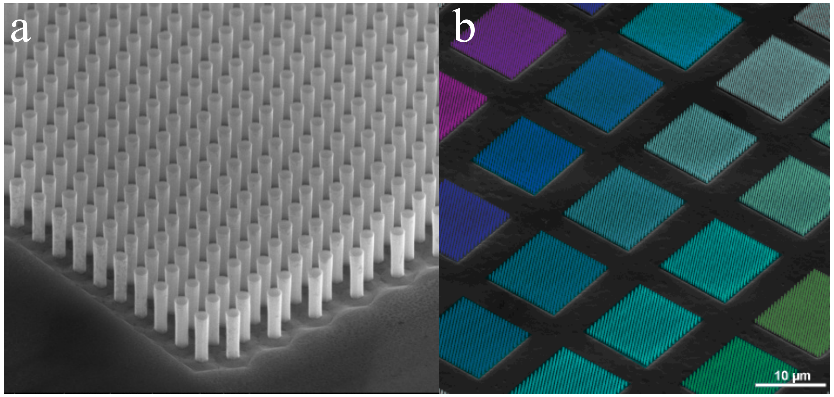


Opal

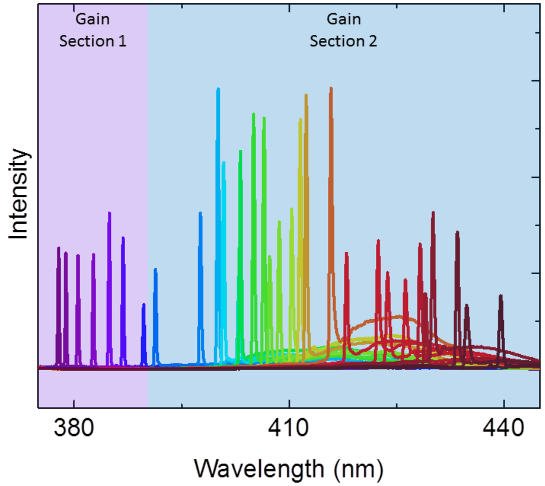
Opalux – Photonic Ink



Multi-color nanowire photonic crystal laser pixels



(a) Single Photonic Crystal Laser. (b) Monolithic array of photonic crystal lasers spanning a 60nm spectral bandwidth (false colored).



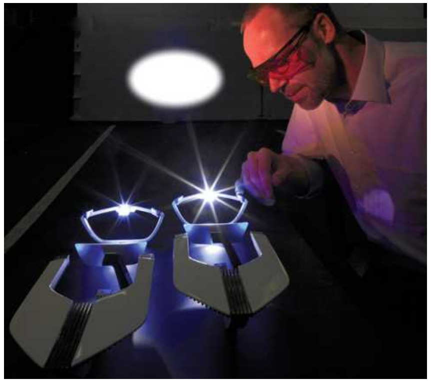
Representative spectra from photonic crystal laser array on chip.

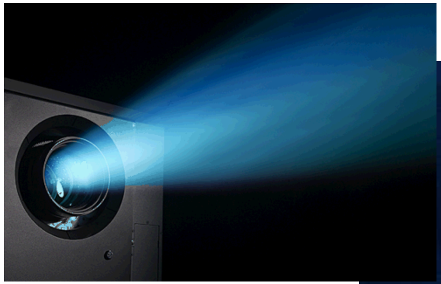
- **Array of photonic crystal NW lasers**
- **Emission wavelength controlled by tuning NW diameters and spacing**
- **60 nm range of emission wavelength on a single integrated chip**
- **Possible applications include SSL, monitor back-lighting, direct-emission displays**

Jeremy B. Wright, et al., Scientific Reports **3,** 2982 (2013).

Future of Lighting: Lasers for Illumination…

Headlights, BMW





Movies

Laser Projector

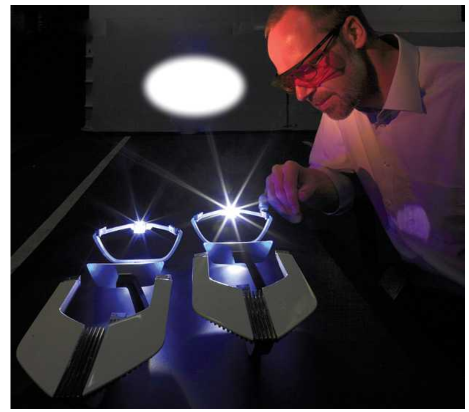
Lasers for Lighting: Automotive Headlights (early niche application)

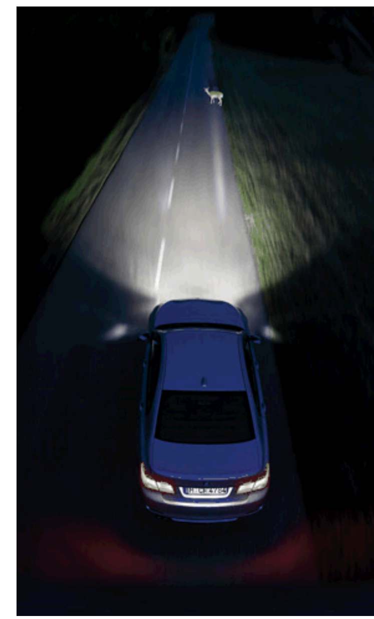
Sandia National Laboratories

- Audi R8 LMX in production
- BMW, shipping later in 2014
- Mercedes concept car

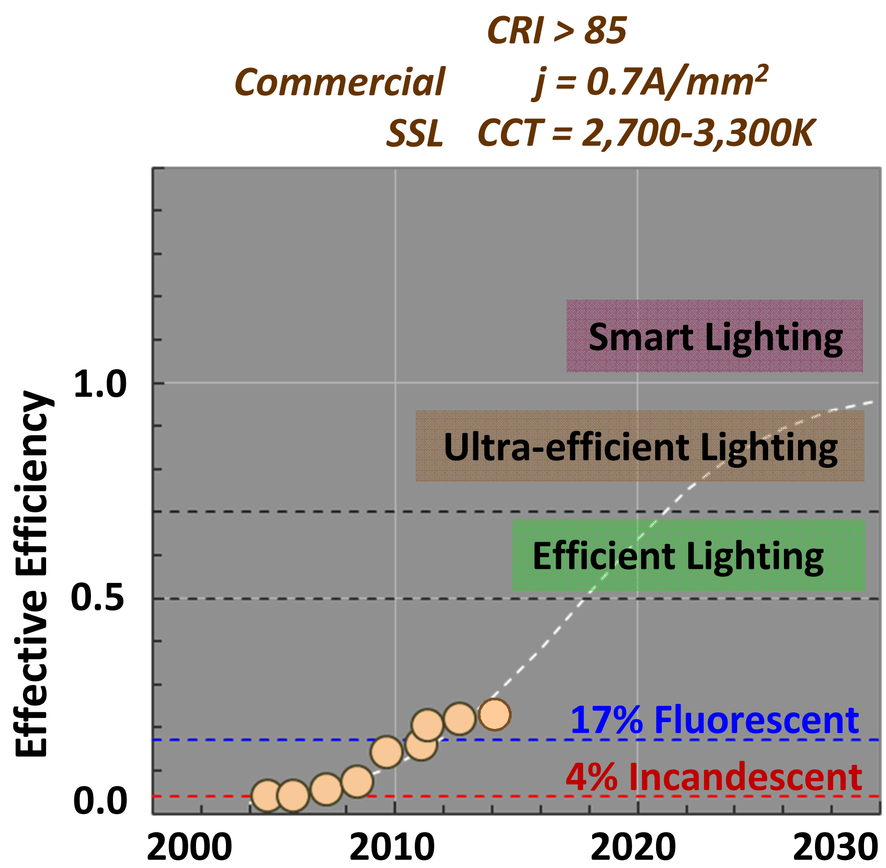
- Applications
  - Dynamic spot lights
  - High & low beams

- Benefits
  - Increased range
  - More compact
  - Increased efficiency
  - New functionality





What if all SSL fixtures were "smart"?



Smart lighting: the "next wave"?

"2nd Wave Lighting: Smart and Feature Rich


Courtesy of E.F. Schubert

Integrated Illumination and Displays

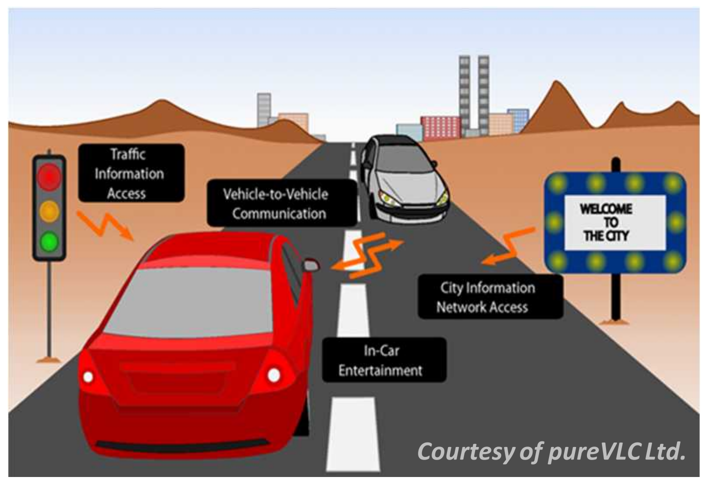

Courtesy of NEONNY Technologies

Human Health, Well Being and Productivity


www.bonfirehealth.com

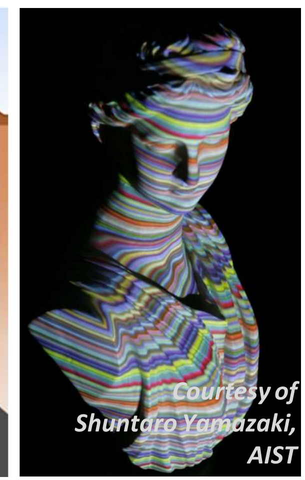

Courtesy of SOA architects

Agriculture



Courtesy of pureVLC Ltd.

Communication


Courtesy of Shuntaro Yamazaki, AIST

Light-Field Mapping

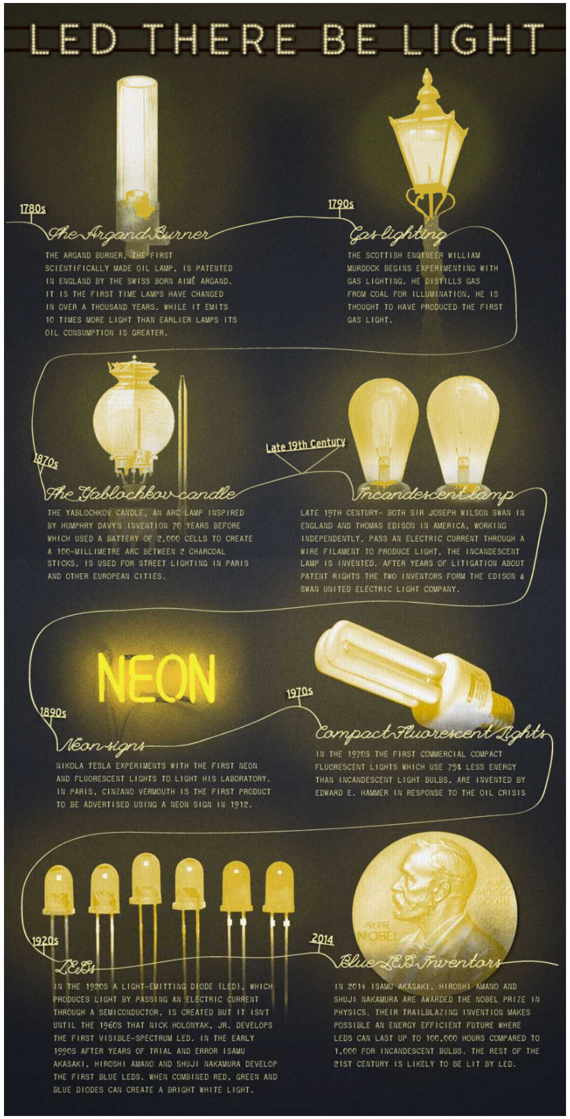
M.H. Crawford, J.J. Wierer, A.J. Fischer, G.T. Wang, D.D. Koleske, G.S. Subramania, M.E. Coltrin, J.Y. Tsao, R.F. Karlicek, Jr., "Solid-State Lighting: Toward Smart and Ultra-Efficient," Advanced Optical Materials (to be published, 2014).

2014 Nobel Prize in Physics



Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura

The Nobel Prize in Physics 2014 was awarded…*"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources*



2015: The International Year of Light

Sandia National Laboratories

United Nations Educational, Scientific and Cultural Organization

International Year of Light 2015

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INTERNATIONAL DARK-SKY ASSOCIATION

Thank You!

Questions?