SAND2014-4318P

*Exceptional service in the national interest*

Sandia National Laboratories

SSLS EFRC
SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

# The Future is Bright for Solid-State Lighting

**Mike Coltrin**

SAND Number 2012-5105 C

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.

U.S. DEPARTMENT OF ENERGY

# Outline of presentation

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

# Why Solid-State Lighting Matters

**<u>Efficiencies of energy technologies in buildings</u>:**

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

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

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

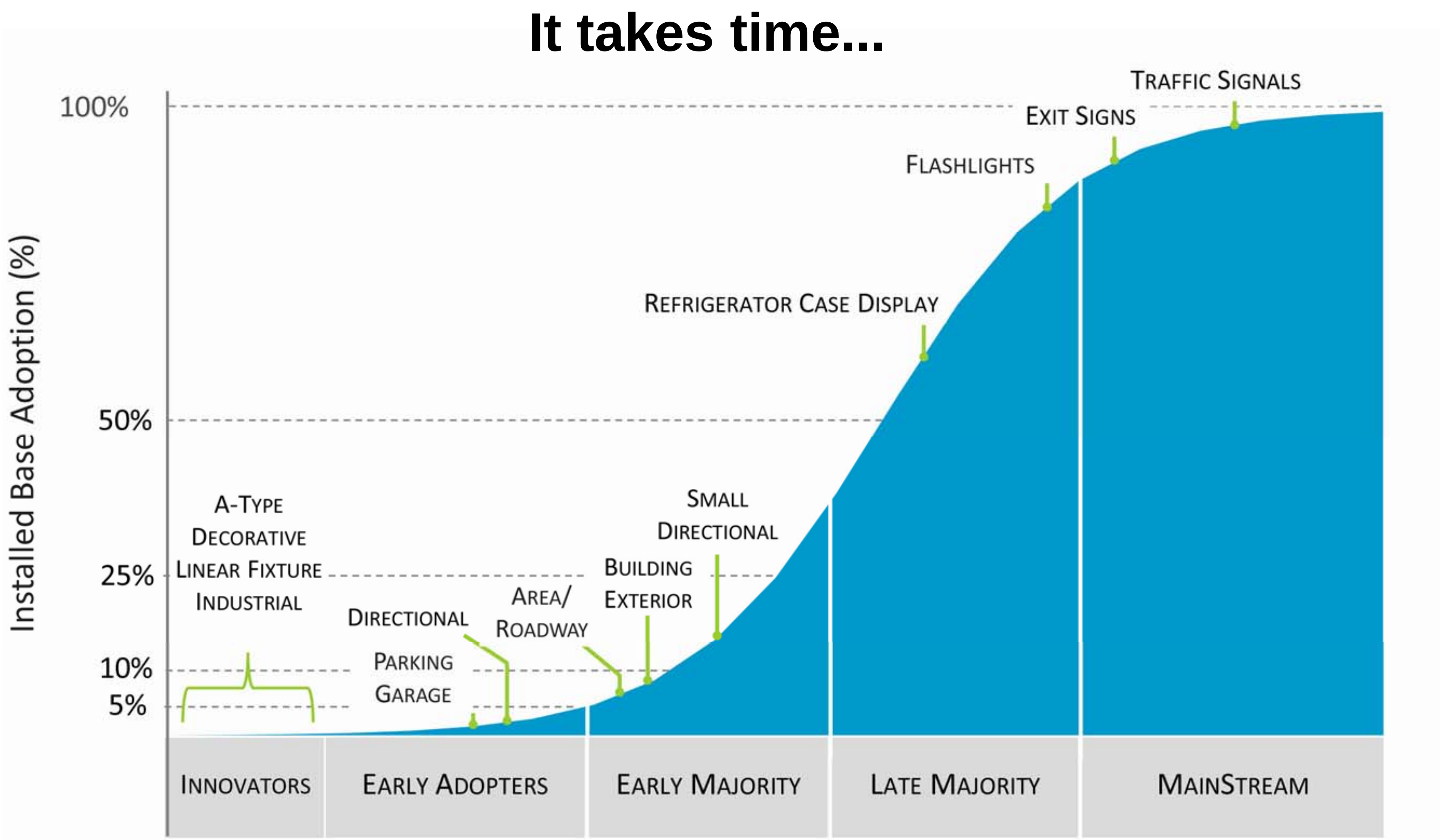
| Projected Year 2030 Savings | US |
|---|---|
| Electricity used (TW-hr) | 300/year |
| $ spent on Electricity | $30B/year |
| Electricity generating capacity (GW) | 50 |
| Carbon emissions (Mtons/year) | 210 |

# Department of Energy SSL Program Goal

## GOAL

**By 2025**, develop advanced SSL technologies that — compared to conventional lighting technologies — are much more energy efficient, longer lasting, and cost competitive, by targeting a product system efficiency of 50 percent with lighting that accurately reproduces sunlight spectrum.

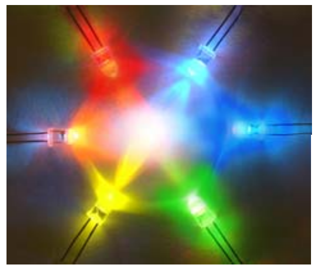
# The Evolution of Adoption

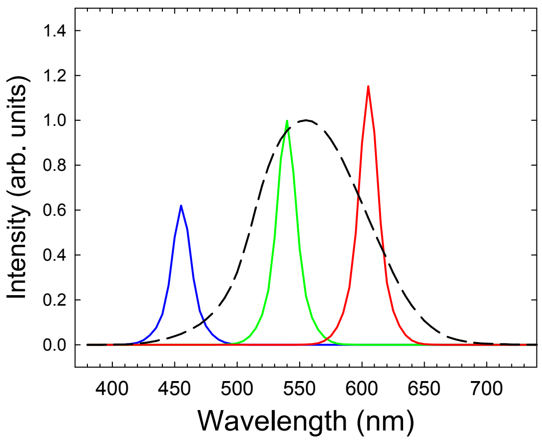


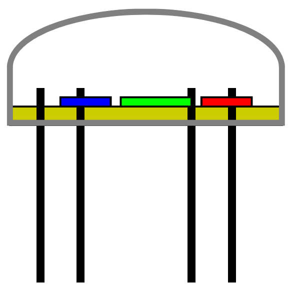
# There are two basic approaches to making a “white” LED

## Multi-LED:

Mix light from multiple LEDs



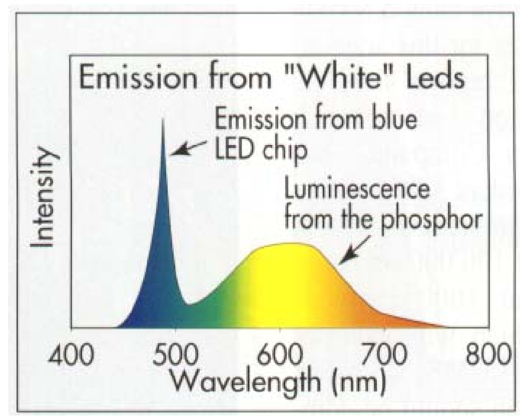


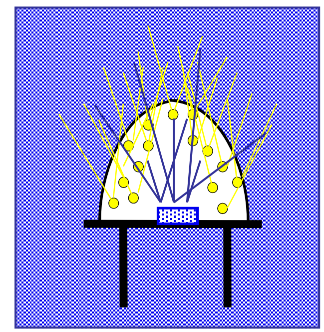



High Control
High Efficiency
High Cost

## LED + Phosphors:

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

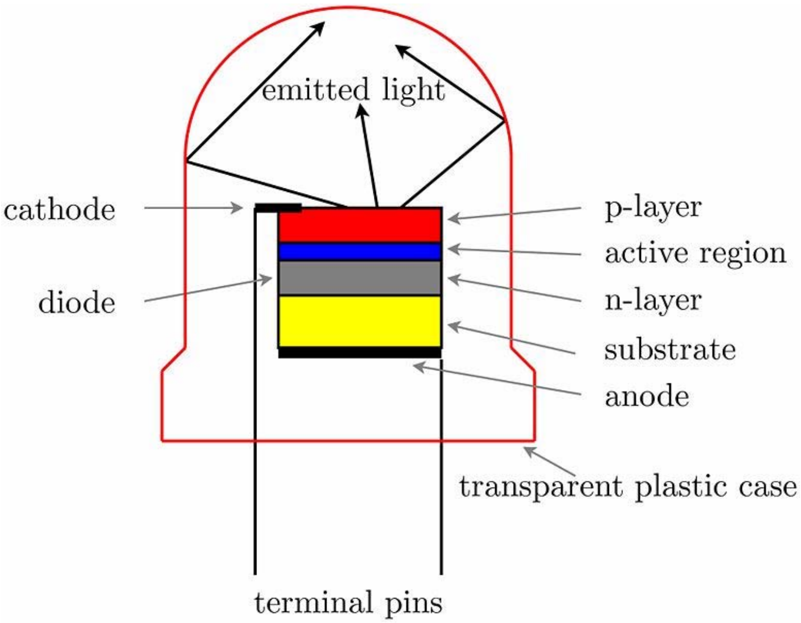


Lower Control
Lower Efficiency
Lower Cost

Blue or UV requires use of gallium nitride (GaN) based material

# How LEDs work




- **An LED is a semiconductor device, i.e., p-n (positive-negative) junction**
- **Current flows from the p-side (anode) to the n-side (cathode)**
- **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

# Competition between Radiative and Nonradiative processes determines LED efficiency

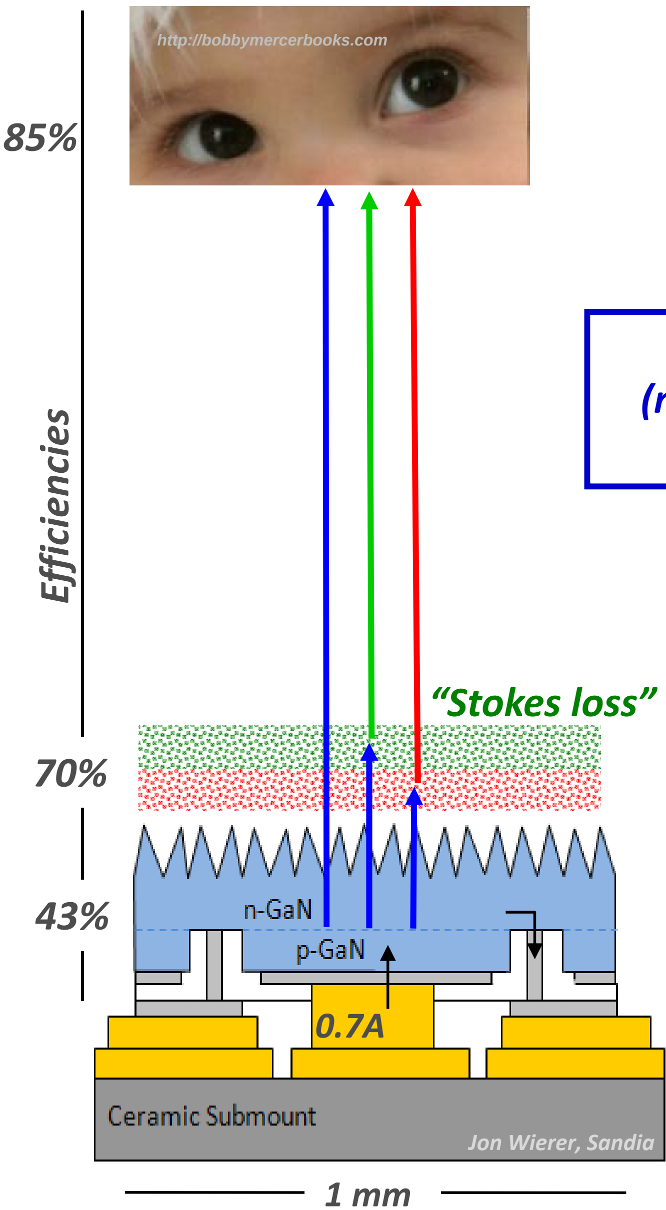
$$\varepsilon_{IQE} = \frac{Bn^2}{An + Bn^2 + Cn^3 + Dn^m + \ldots}$$

- $An$: 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, $\boldsymbol{n}$

# Why is SSL only ~25% Efficient?

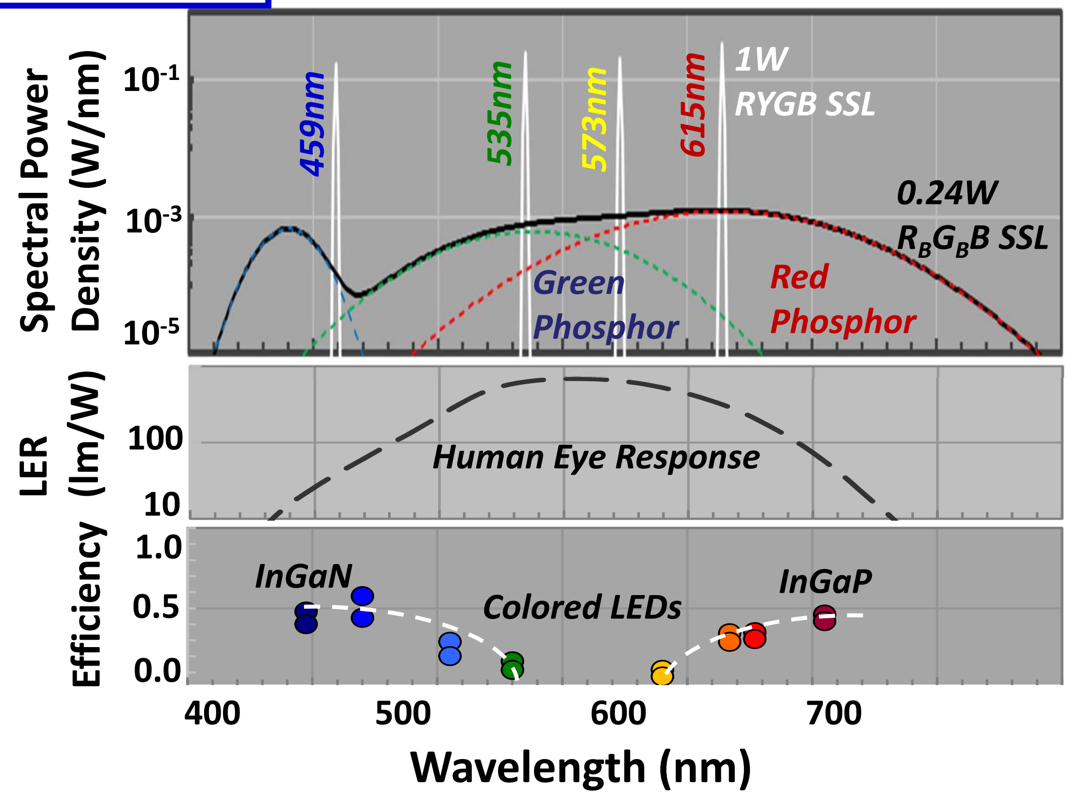
## Technology Grand Challenges



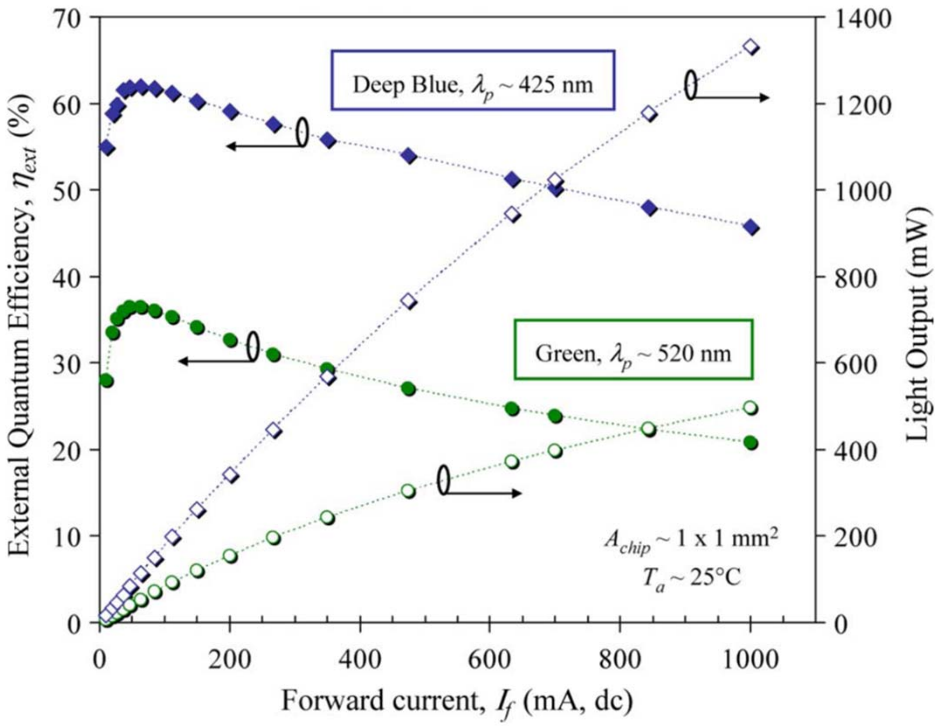

*1. Efficiency Droop (near-100% efficiency at all currents)*

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

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



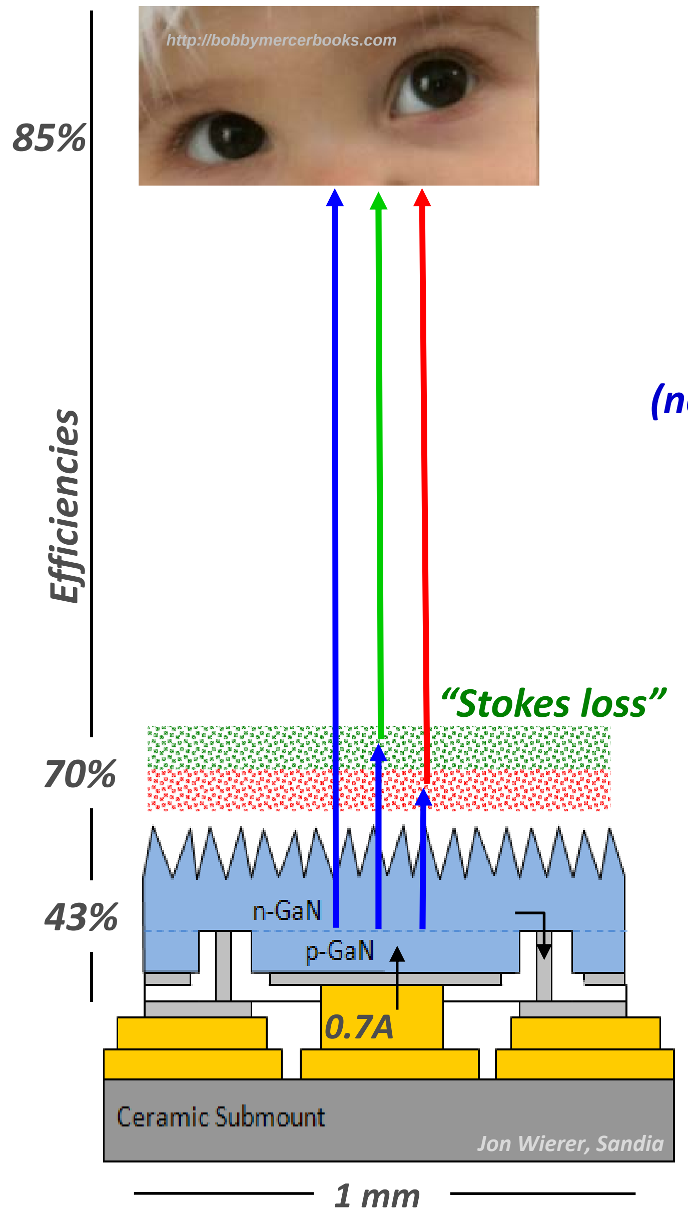
# LED "Efficiency Droop" at High Currents




- 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

# Why is SSL only ~25% Efficient?

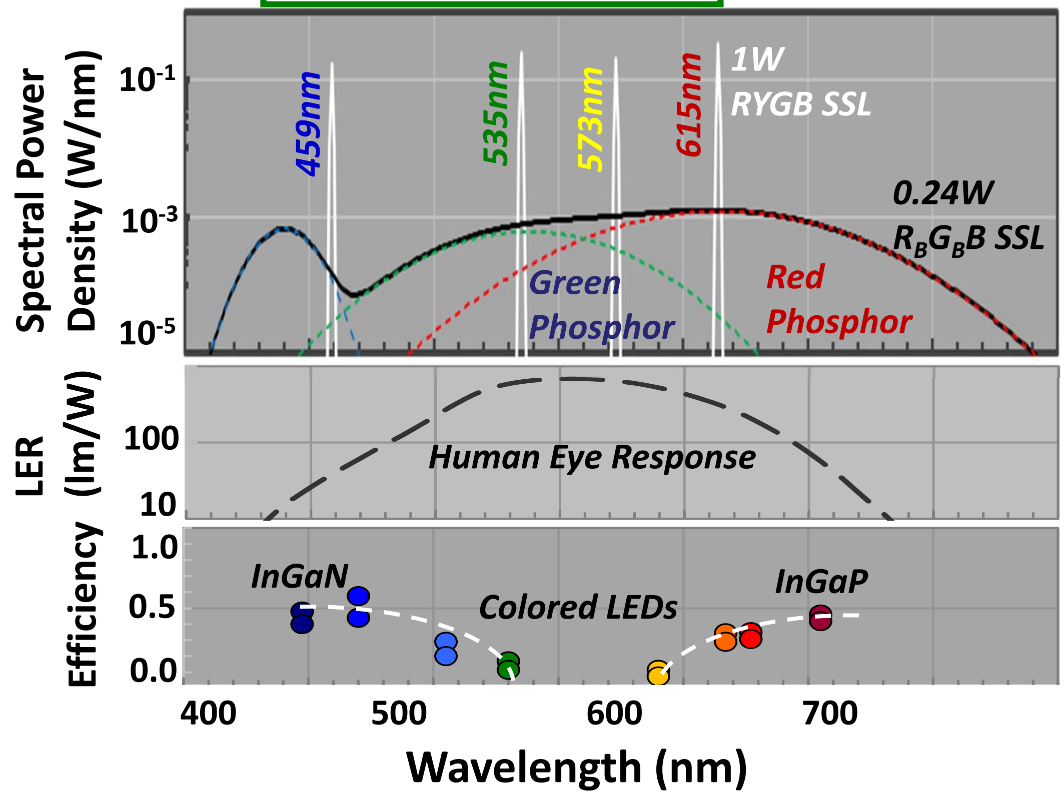
## Technology Grand Challenges



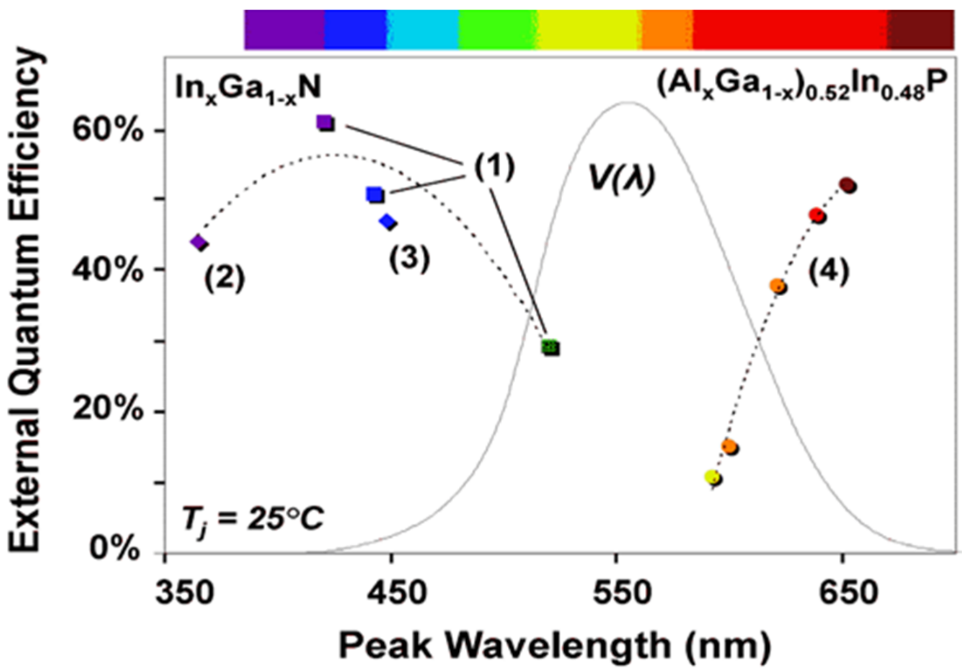

1. Efficiency Droop (near-100% efficiency at all currents)

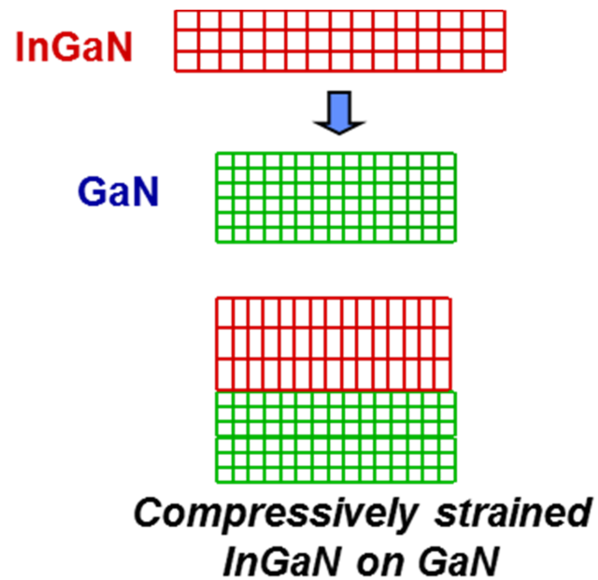
2. Green-Yellow Gap (near-100% efficiency at all wavelengths)

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



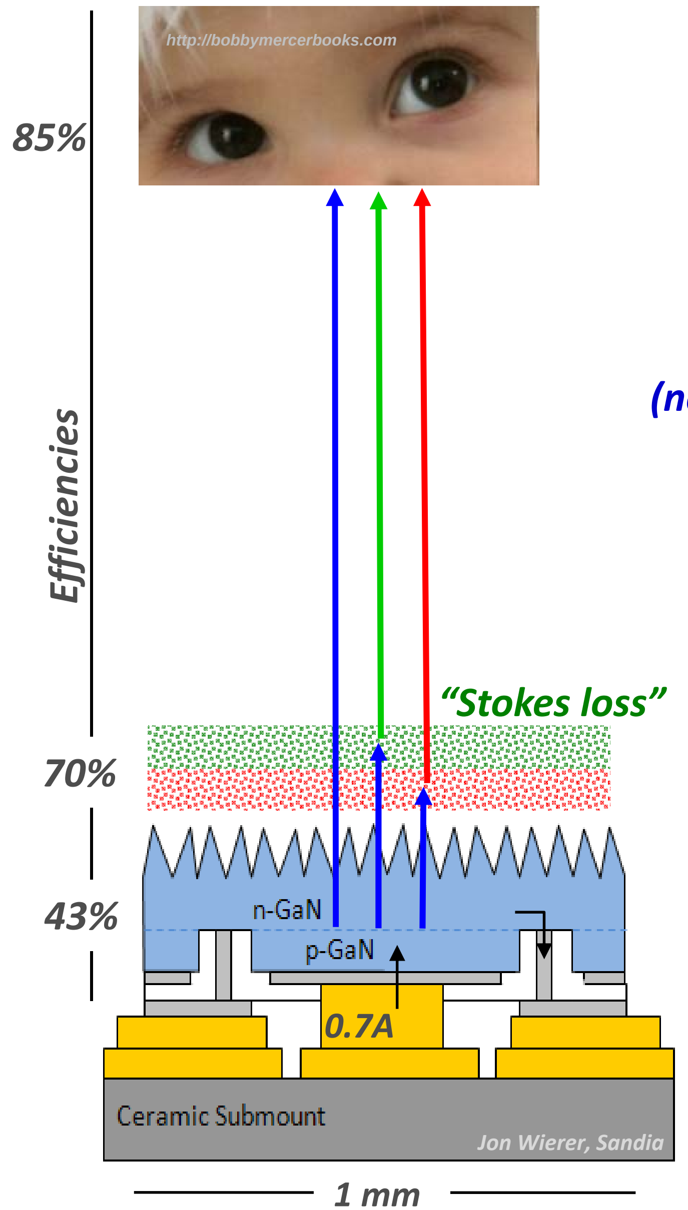
# LED efficiency drops as Indium content of InGaN is increased (the "Green Gap")



# Why is SSL only ~25% Efficient?

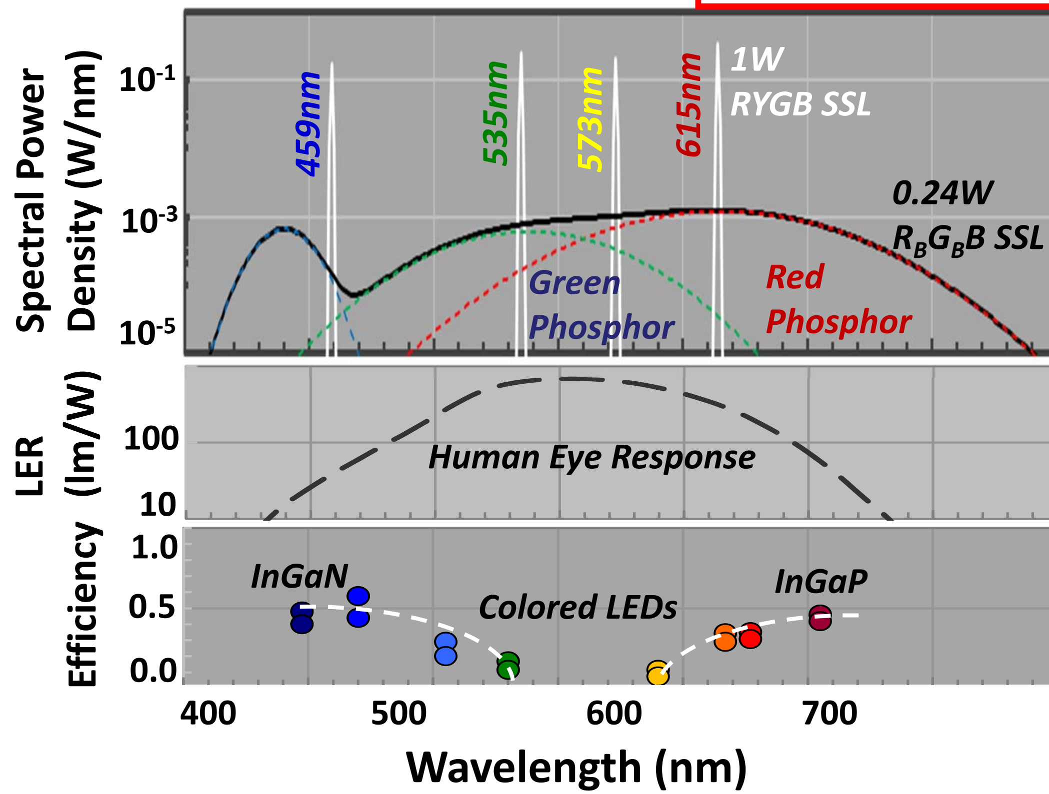
## Technology Grand Challenges




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

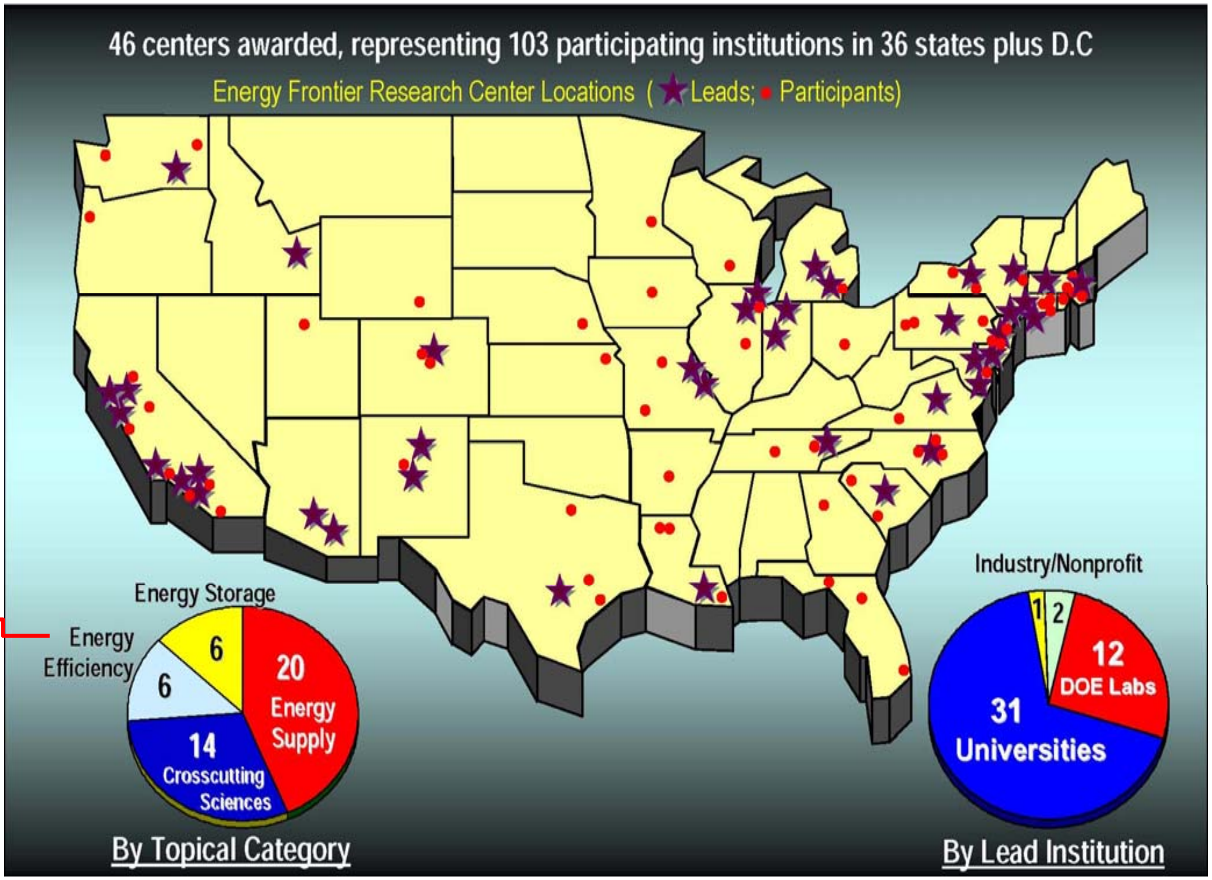
*2. Green-Yellow Gap (near-100% efficiency at all wavelengths)*

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



# Solid-State Lighting Science EFRC

- We are one of 46 Department of Energy Office of Science EFRCs
- Our Budget: $18M over 5 years beginning Aug 2009
- We are one of 6 EFRCs focused on efficiency, and the only one focused on SSL



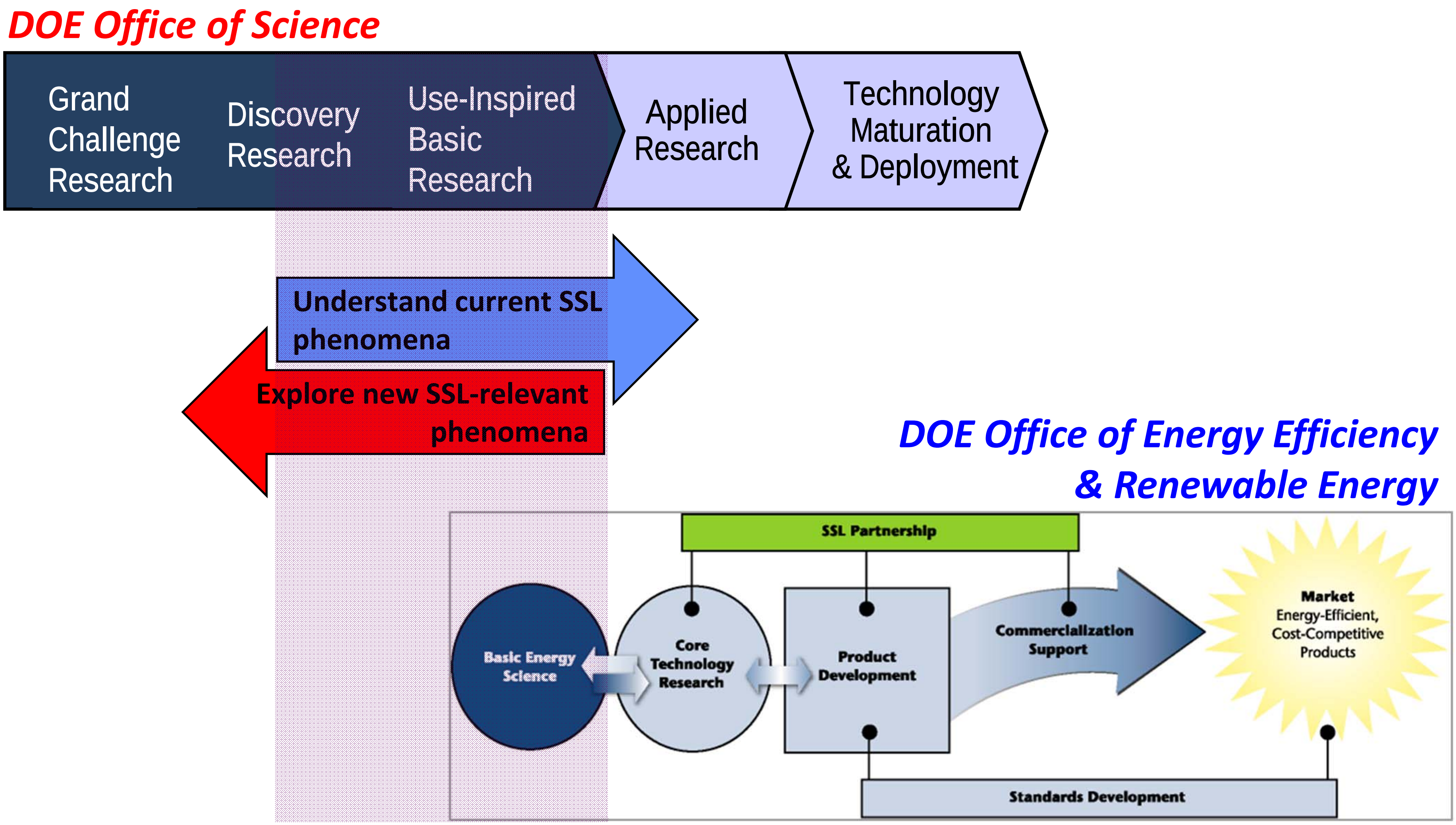
# SSLS EFRC high-level stats

- Lead institution: Sandia National Labs
- Budget: $3.6M/yr for 5 years
- Staffing (48)
  - Sandia staff / students (27)
  - University partners / students (16)
  - Sandia admin/business support (5)
- Leadership
  - Director: Mike Coltrin
  - Chief Scientist: Jeff Tsao

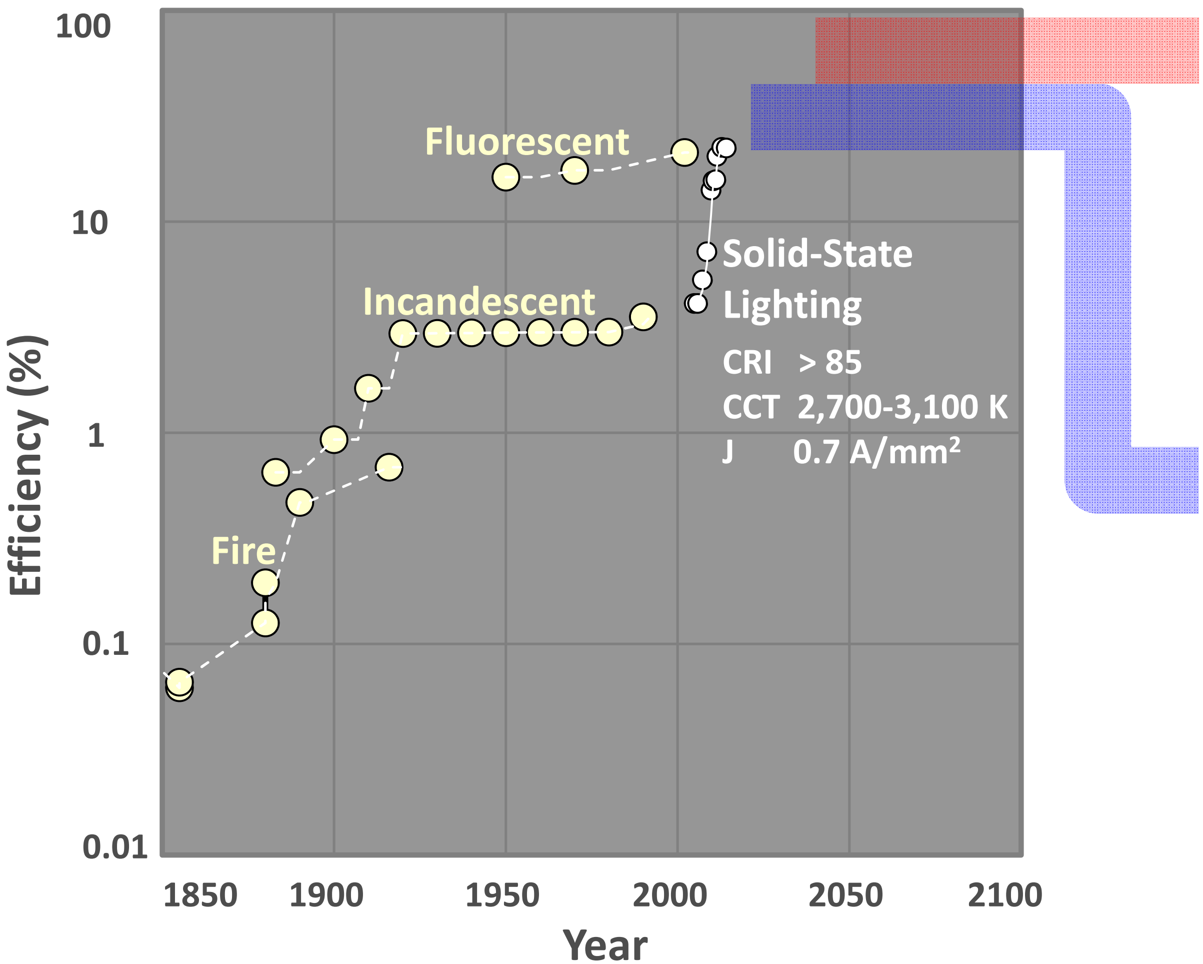
Sandia National Laboratories
THE UNIVERSITY of NEW MEXICO
UCI University of California, Irvine
Northwestern University
UCSB
UNIVERSITY OF CALIFORNIA UCMERCED
PHILIPS
Los Alamos NATIONAL LABORATORY

M. E. Coltrin, et al., Journal of Physical Chemistry C, **118** (to appear June 26, 2014)

# SSLS EFRC: Use-Inspired Basic Research



# Solid-State Lighting: Two Future Scenarios




**SSLS EFRC: 75-100%**

**Enables the greatest energy savings (current paradigm cannot achieve)**

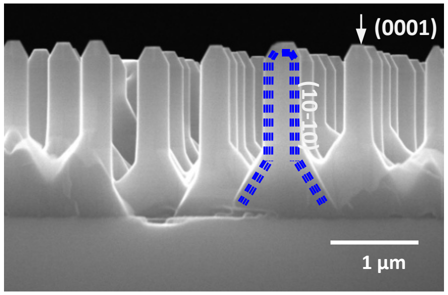
**EERE Programs: 25-50%**

**Enables penetration of traditional lighting (well on its way)**

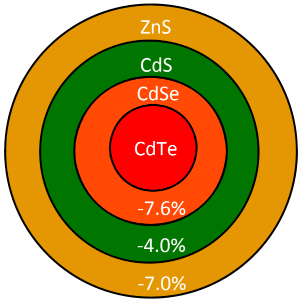
# SSLS EFRC Research Thrusts

Materials Architectures

**1: Nanowires**




**2: Quantum Dots & Phosphors**



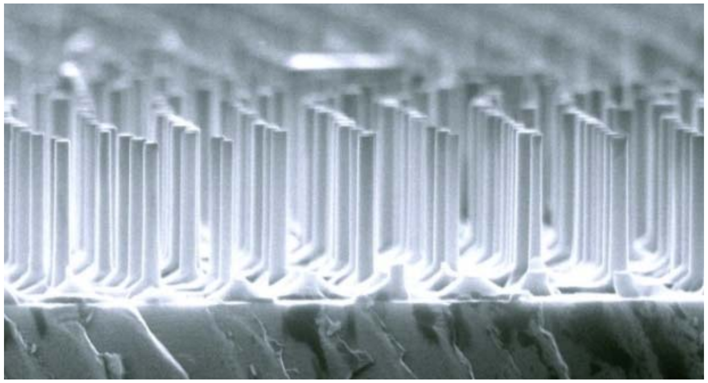

Light Emission Phenomena

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

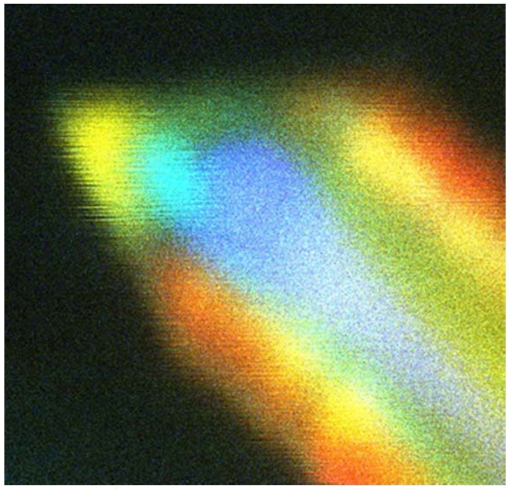
**3: Defects in InGaN Materials**

**4: Enhancing Emission Rates**

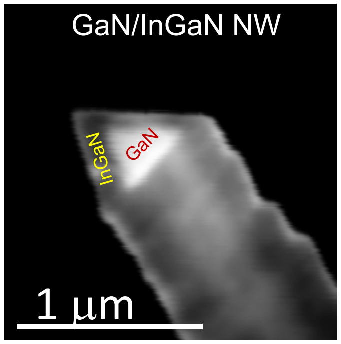
# Radial InGaN/GaN nanowires show promise for addressing the green-yellow-red gap



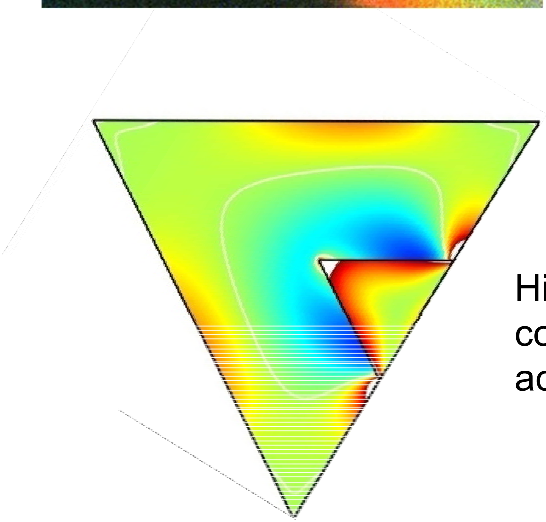
Array of nanowires with controlled height, diameter, and spacing (height ~3 $\mu$m; diam. ~100 nm)



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




1-D geometry can accommodate lattice-mismatch strain

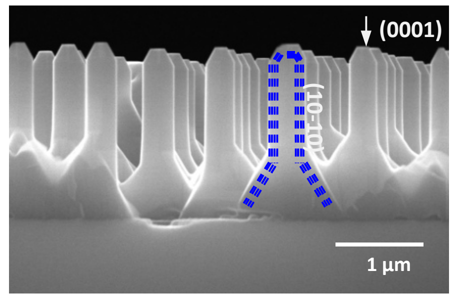


Highest In-content at corners, which can accommodate strain

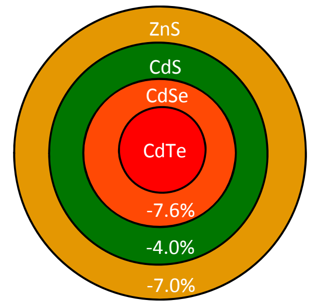
# SSLS EFRC Research Thrusts

Materials Architectures

1: Nanowires




2: Quantum Dots & Phosphors



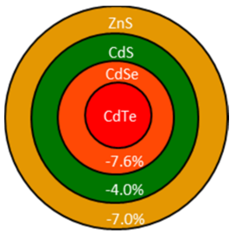

Light Emission Phenomena

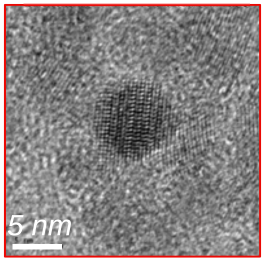
$$\varepsilon_{IQE} = \frac{Bn^2}{An + Bn^2 + Cn^3 + Dn^m + \ldots}$$

3: Defects in InGaN Materials

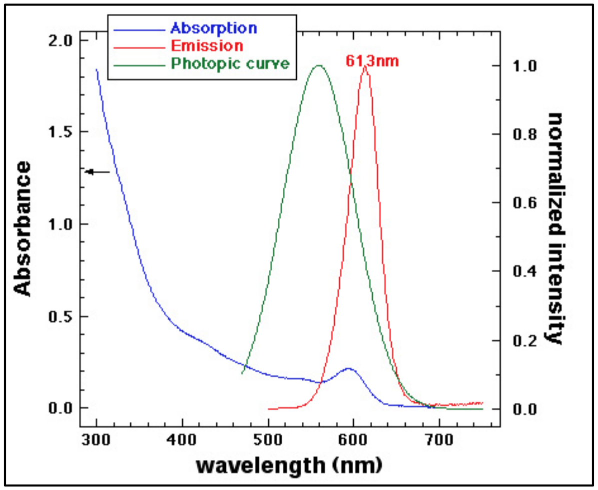
4: Enhancing Emission Rates

# Narrow linewidth red quantum dot emitters for solid-state lighting



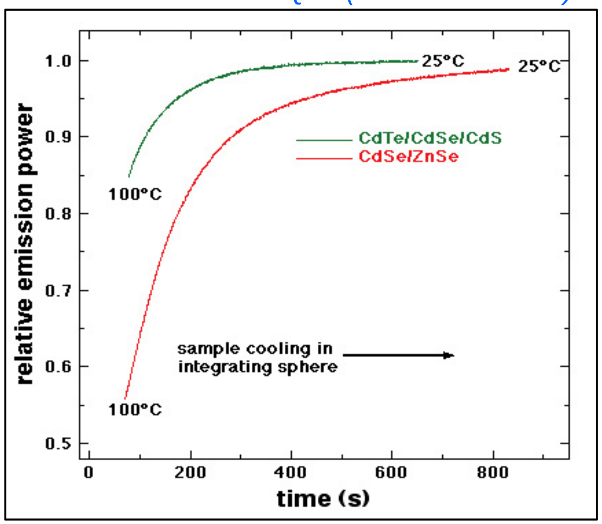




*TEM image of CdTe core coated with 10 CdSe shells.*




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

Emission centered at 613 nm, ideal for SSL applications




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

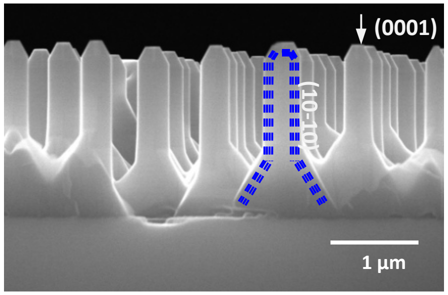
Core / Shell / Shell QD structure shows much less efficiency-quenching at SSL operating temp.


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

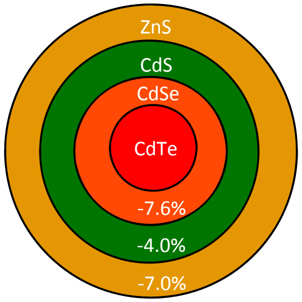
# SSLS EFRC Research Thrusts

Materials Architectures

1: Nanowires




2: Quantum Dots & Phosphors



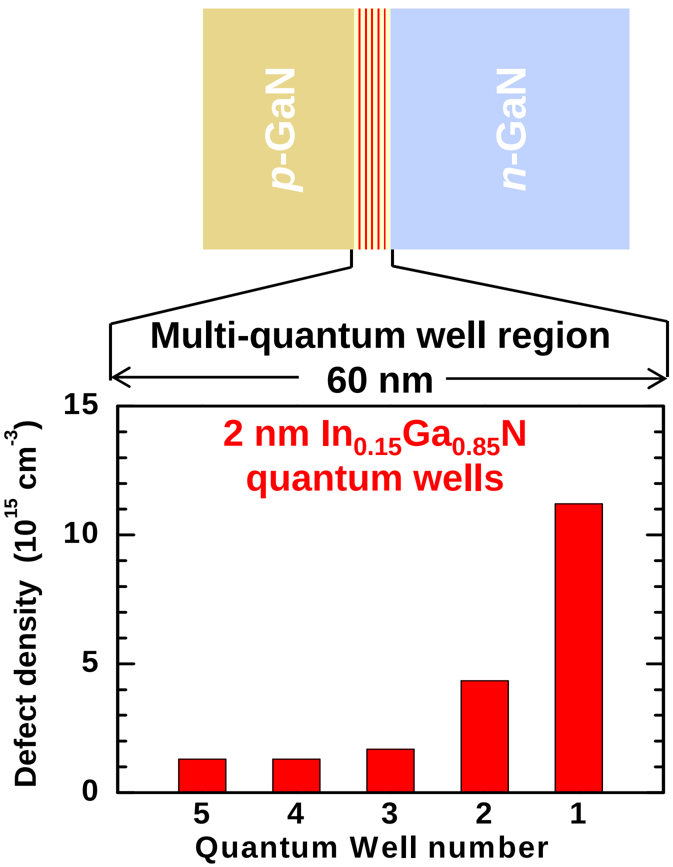

Light Emission Phenomena

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

3: Defects in InGaN Materials

4: Enhancing Emission Rates

# Quantitative, nano-scale depth profiling of defects in InGaN LEDs



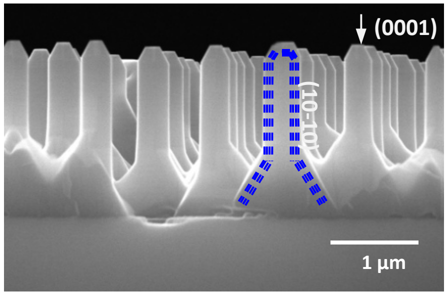

- **Deep-level optical spectroscopy tool was developed to measure defect density in individual quantum wells**
- **Crystal defects in the thin (~2nm) QWs reduce the LED efficiency**
- **Poor material quality in the "first QW" (at a material interface) yields highest defect density**

A. Armstrong, T.A. Henry, D.D. Koleske, M.H. Crawford, S.R. Lee, *Optics Express* **20**, A812 (2012)

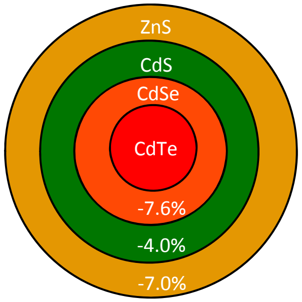
# SSLS EFRC Research Thrusts

**Materials Architectures**

**1: Nanowires**




**2: Quantum Dots & Phosphors**



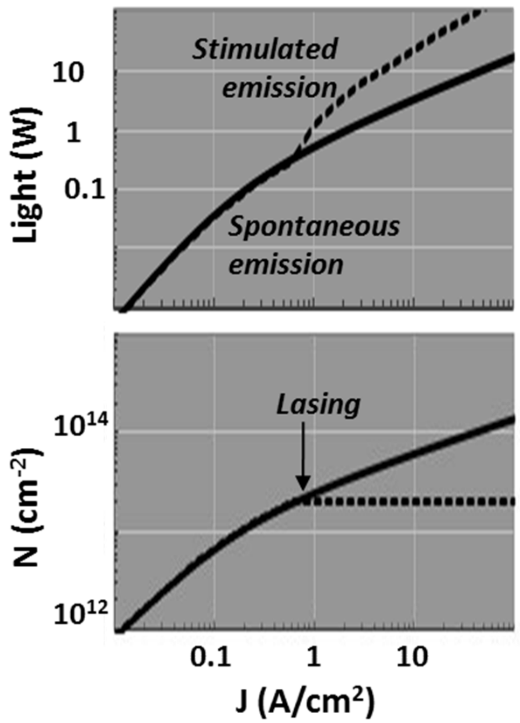

**Light Emission Phenomena**

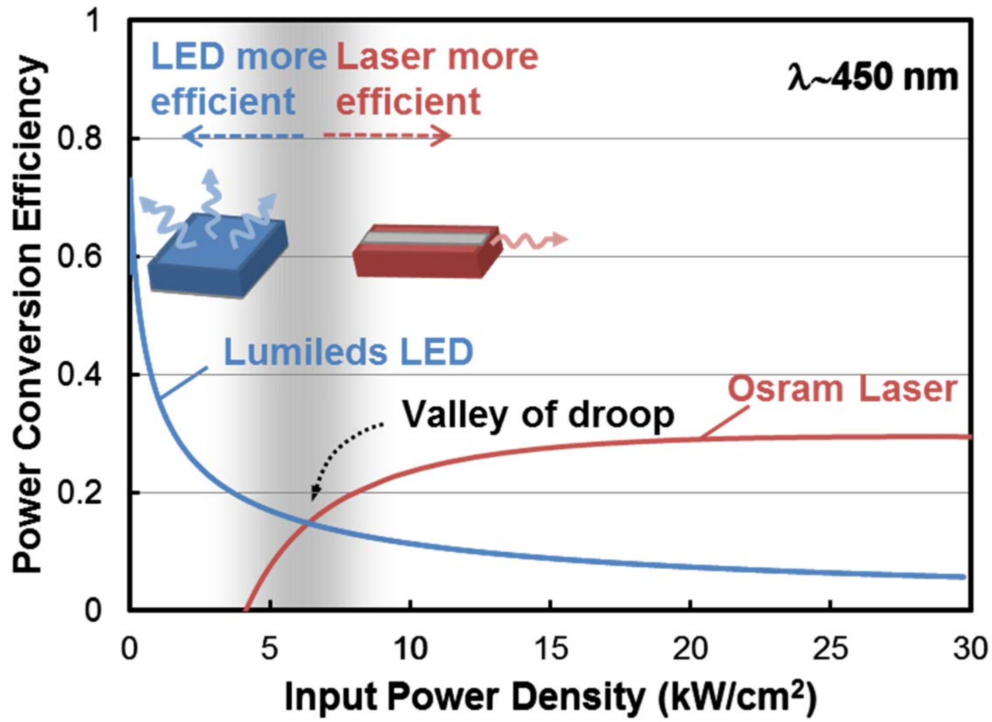
$$\varepsilon_{IQE} = \frac{Bn^2}{An + Bn^2 + Cn^3 + Dn^m + \ldots}$$

**3: Defects in InGaN Materials**

**4: Enhancing Emission Rates**

# Could lasers be part of the solution?



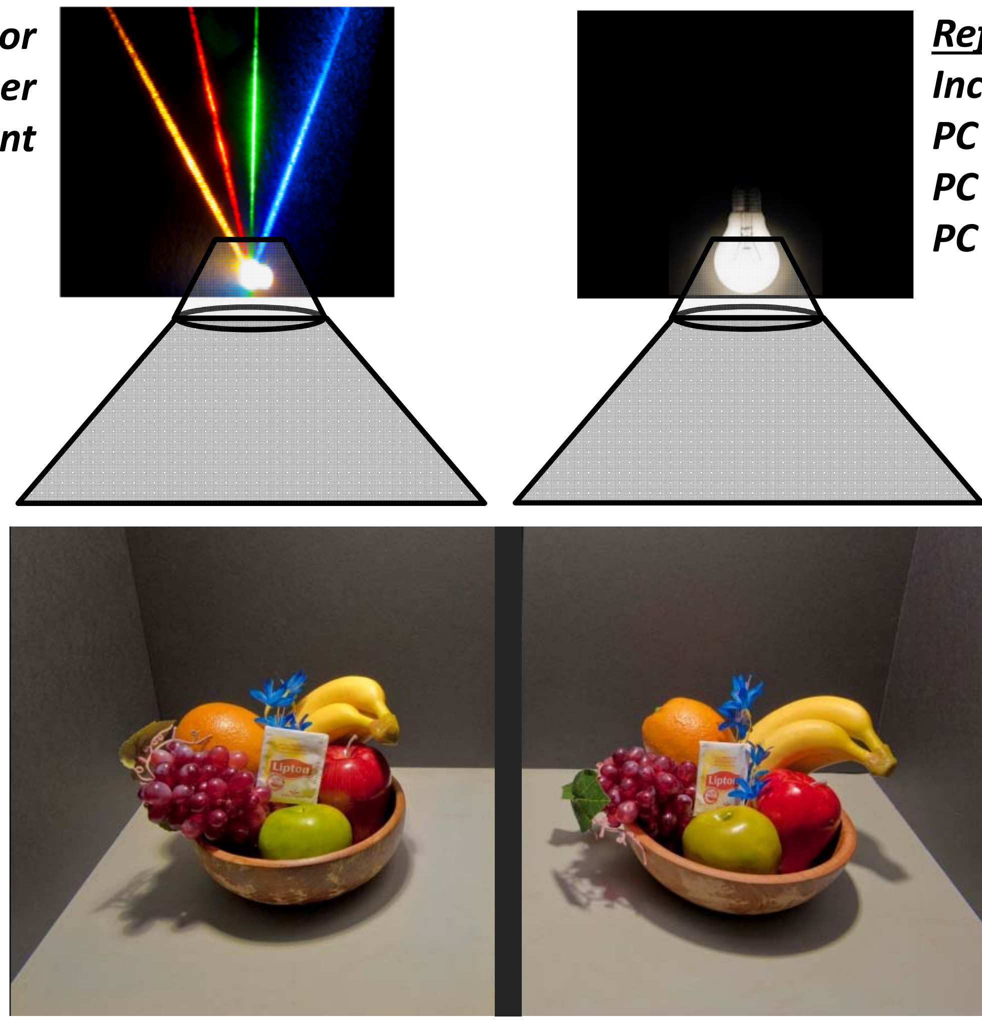




- After threshold lasers are not affected by efficiency droop
- Lasers are more efficient at higher input power densities
- Research needed to lower threshold / improve efficiency
  - InGaN materials; device designs (nano???)

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

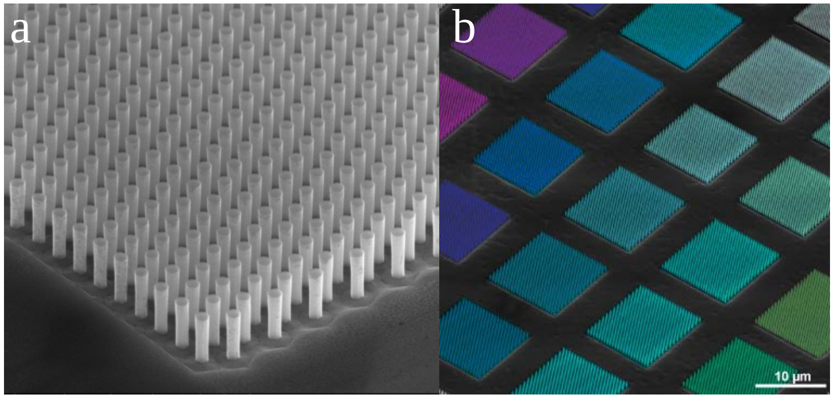
***4-Color Laser Illuminant***

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

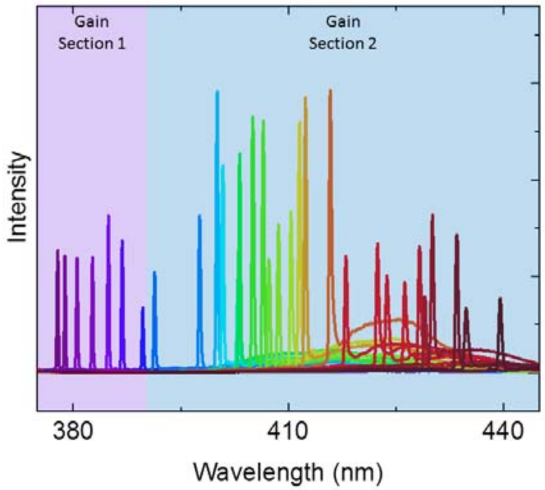


A. Neumann, et al., "Four-color laser white illuminant demonstrating high color-rendering quality," Optics Express **19**, A982-A990 (2011).

# 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**

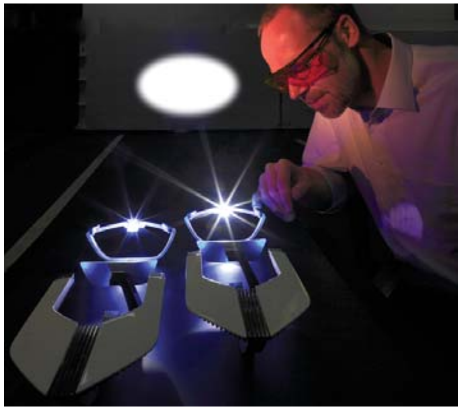
Jeremy B. Wright, et al., Scientific Reports **3,** 2982 (2013).

# Lasers for Lighting:
# Automotive Headlights (early niche application)

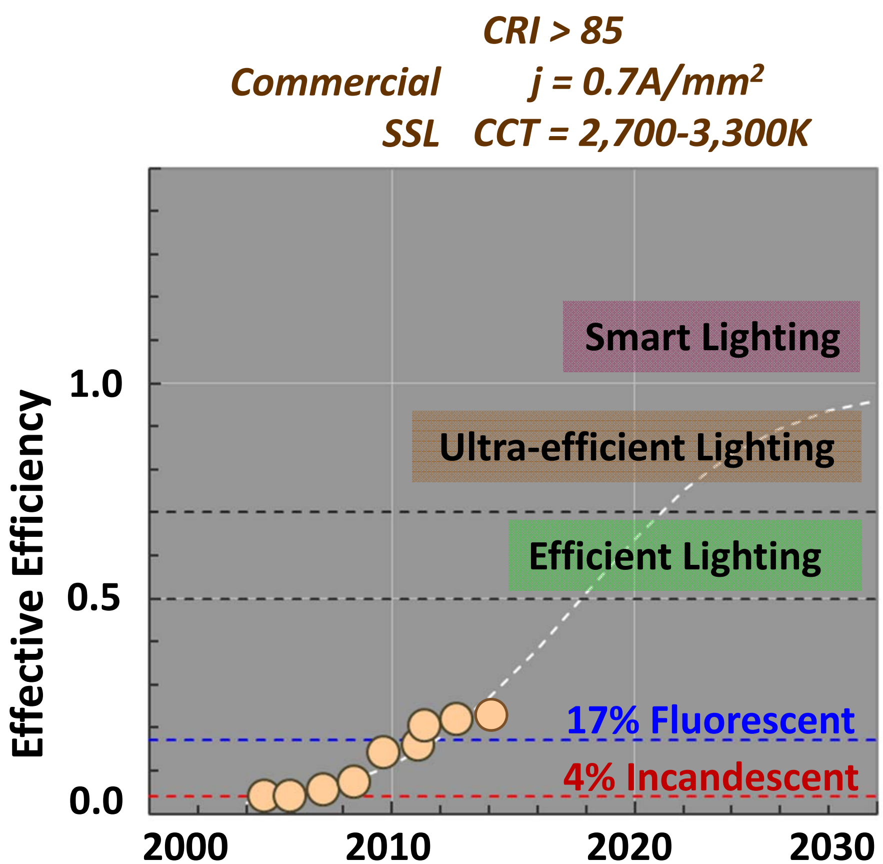
- Audi R8 LMX in production
- BMW, shipping later in 2014
- Mercedes concept car

- 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*

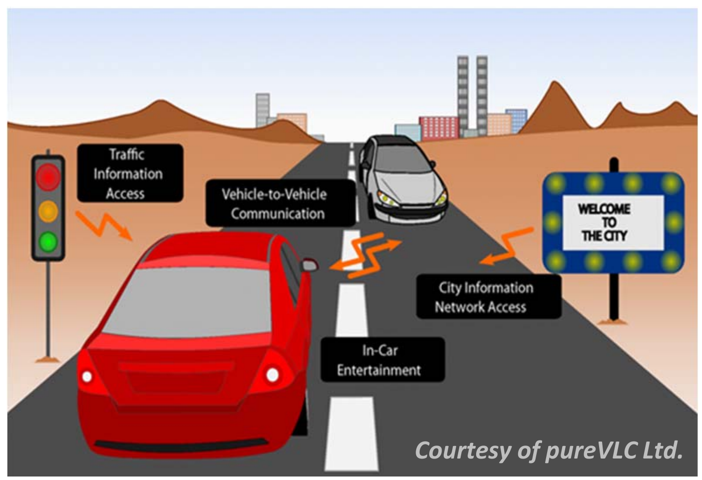
Courtesy of NEONNY Technologies

*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).