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Limits on the maximum attainable efficiency for solid-state lighting

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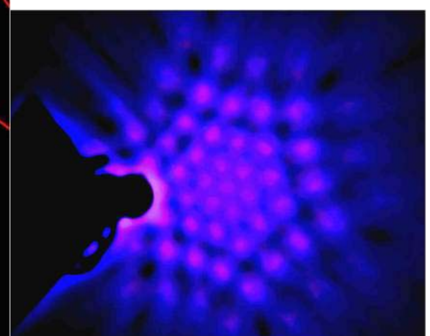

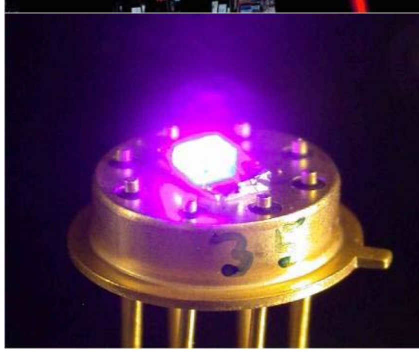

Sandia Solid State Lighting

Illumination through semiconductor science

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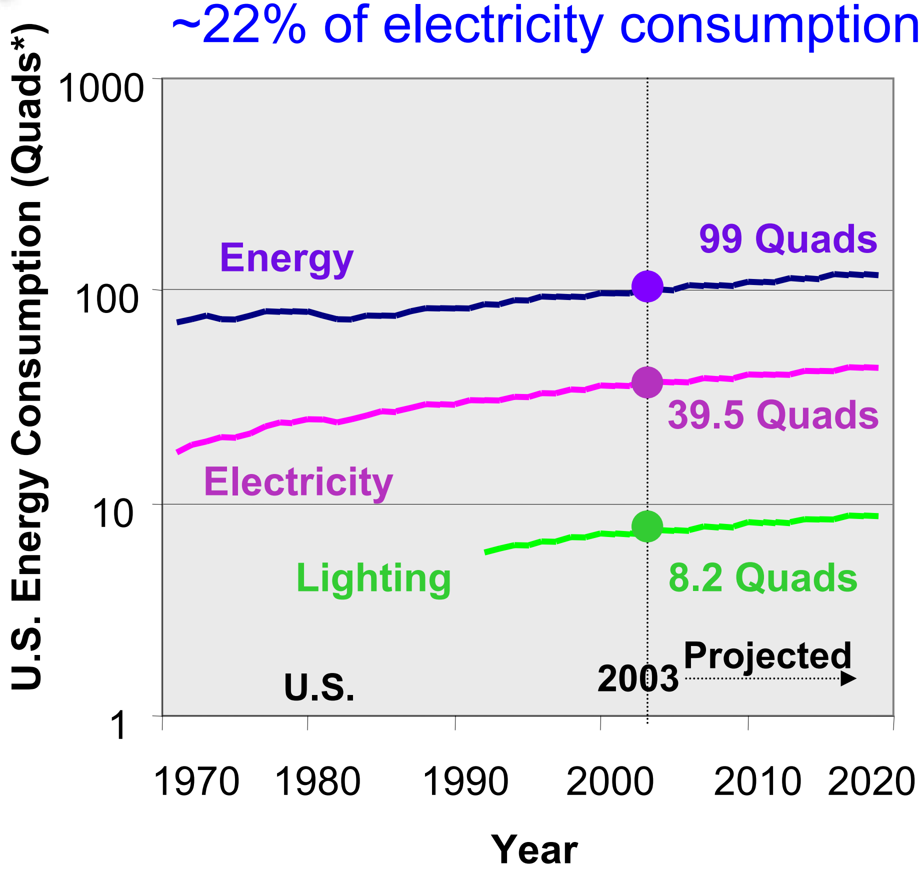
Lighting is a large fraction of energy consumption, and is low efficiency

~22% of electricity consumption is for general illumination



Efficiencies of energy technologies in buildings:

Heating:	70 - 80%
Elect. motors:	85 - 95%
Fluorescents:	**25%**
Incandescents:	**5%**

Lighting is a highly attractive target for reducing energy consumption.

(*1 Quad = 91 TWatt-hr)

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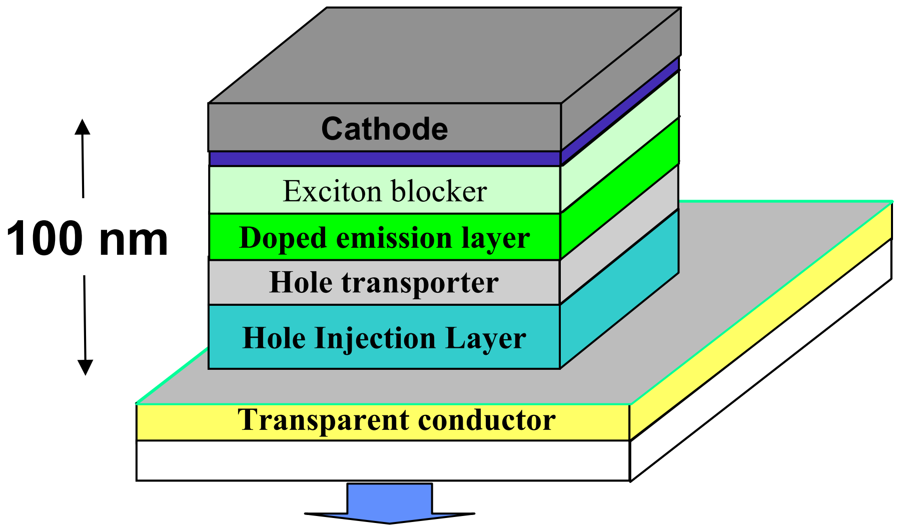
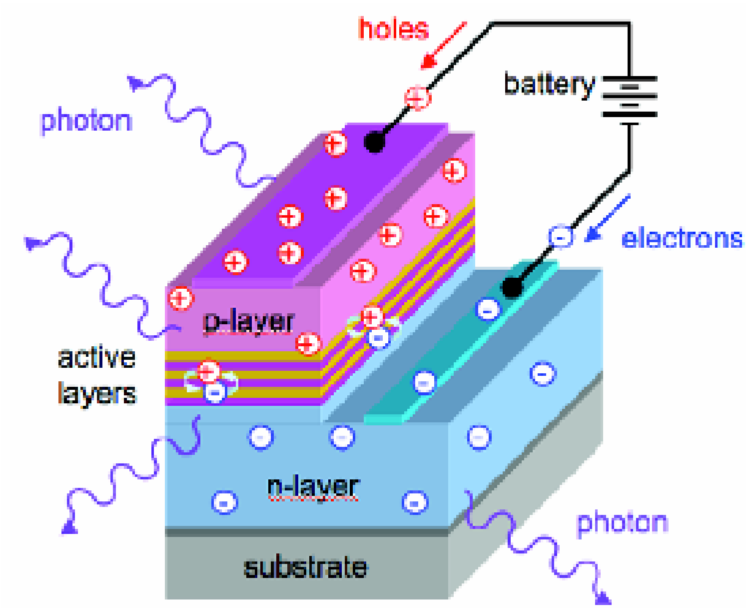
Today, there are two main approaches to solid-state lighting



Organic
(OLED)



Inorganic
(LED)

OLEDs

- Compatible with low energy, large area manufacturing
- Large area emitters => no fixture required
- Epitaxy not required; permits three dimensional assembly of circuits

MP-3 players

Headsets

Current Products

Future Products

General Electric: 2 ft OLED panel, 1200 lm at 7 lm/w

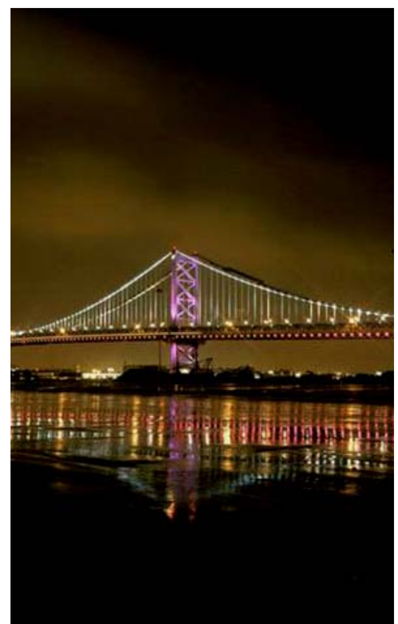
40" Active Matrix OLED Panel

LEDs

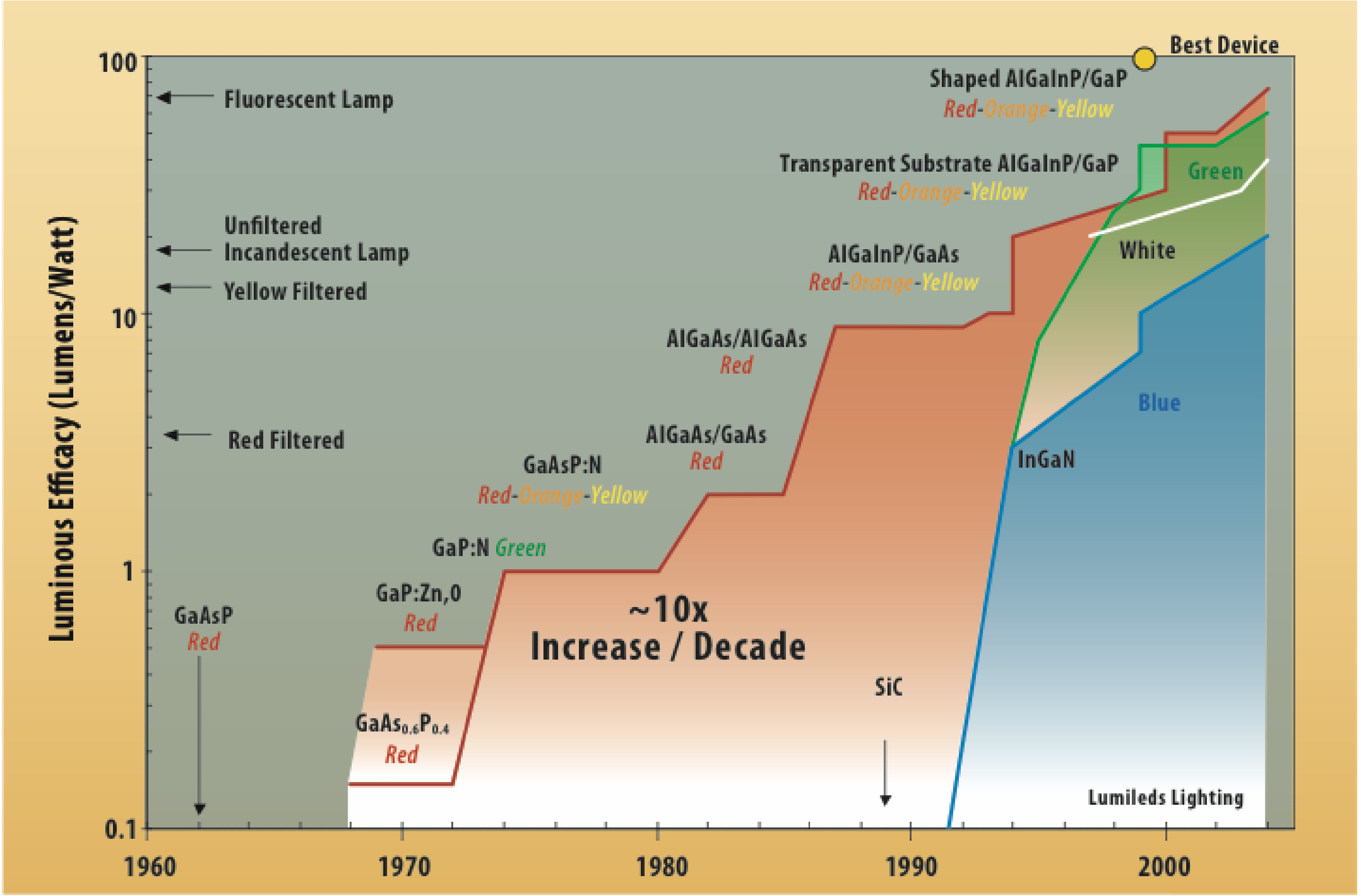
LEDs are already superior for monochrome applications

- **Sophisticated semiconductor manufacturing needed**
- **Extremely bright, small area sources => fixture required**
- **Epitaxial growth required**

NASDAQ Giant Video Display
Times Square NY (Jeff Tsao)



LEDs have been increasing in efficiency (and dropping in cost) following a Moore's Law



RED: lm/W has improved at 10X/decade, cost has decreased at 10X/decade.

(*Courtesy of M. G. Craford, LumiLeds)

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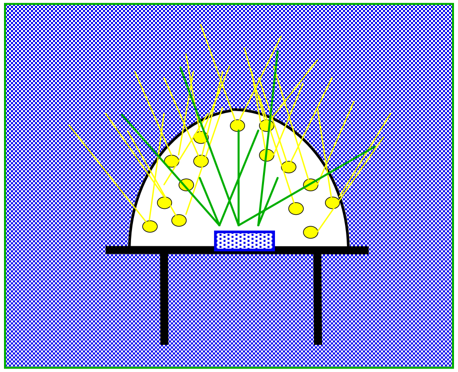
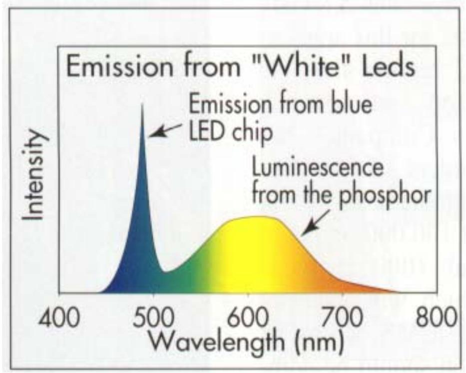
How to make a white LED

- **UV/Blue InGaN LED-pumped phosphors**





Commercial approach (to date).
Up to 150 lm/W achieved*
…relatively low cost
*** Nichia**

CRI of blue LED + yellow phosphor is ~70

- **Multi-chip/ multi-color LEDs (RGB)**

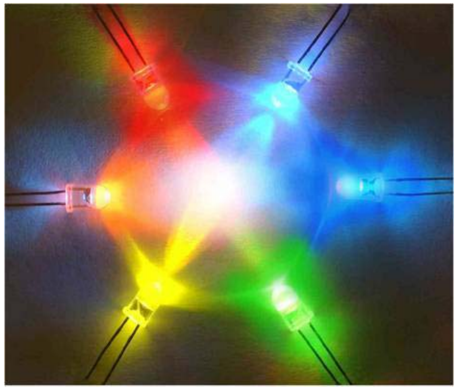
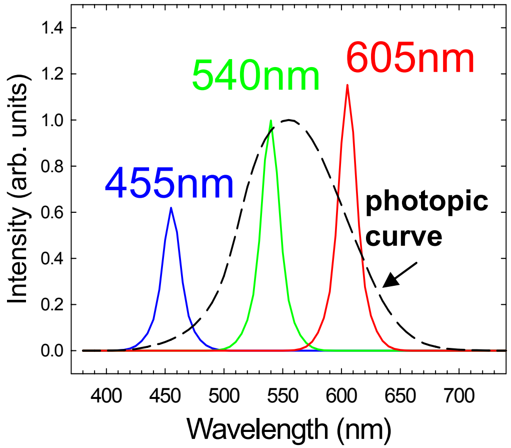


Figure courtesy of E. F. Schubert



Potentially most efficient, highest quality white lighting approach
…but high cost

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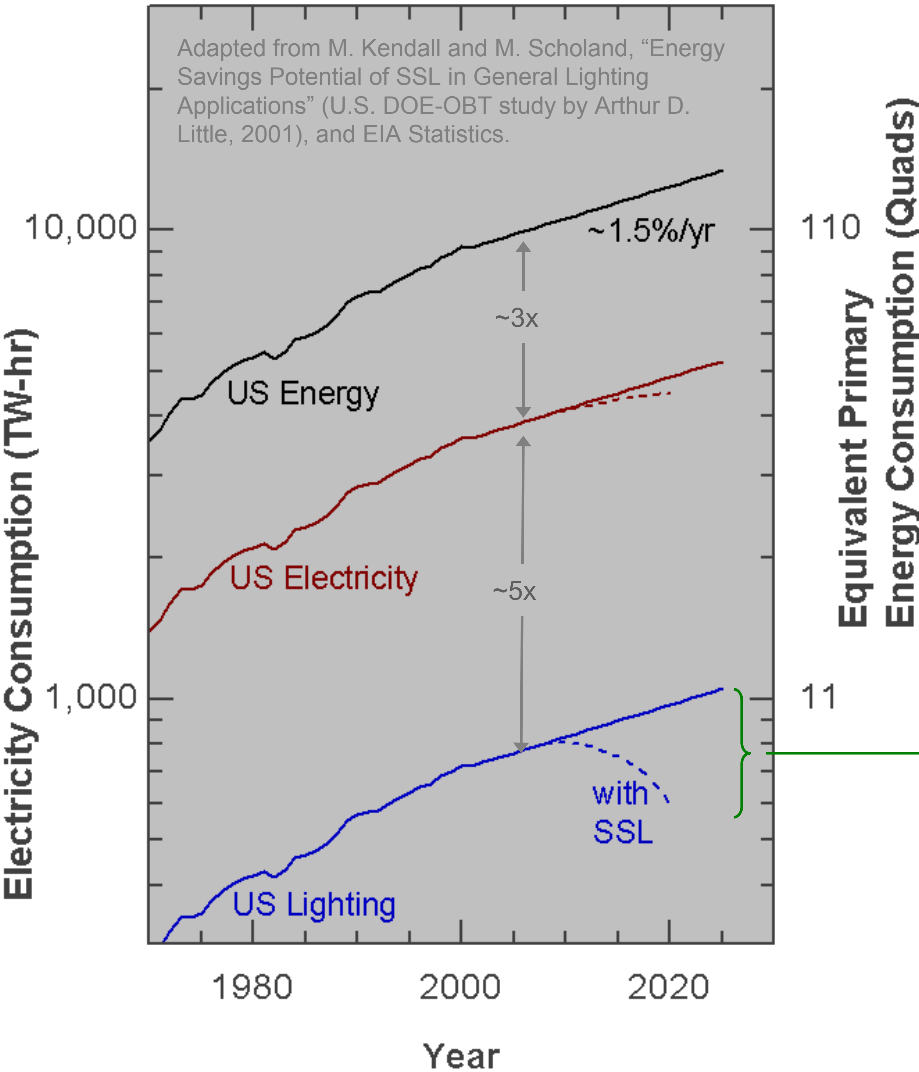
U.S. Department of Energy SSL goal

DOE/EERE Solid-State Lighting Program Goal

By 2025, develop advanced solid-state lighting 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 the sunlight spectrum.*

http://www.netl.doe.gov/ssl

Potential energy and carbon savings from solid-state lighting

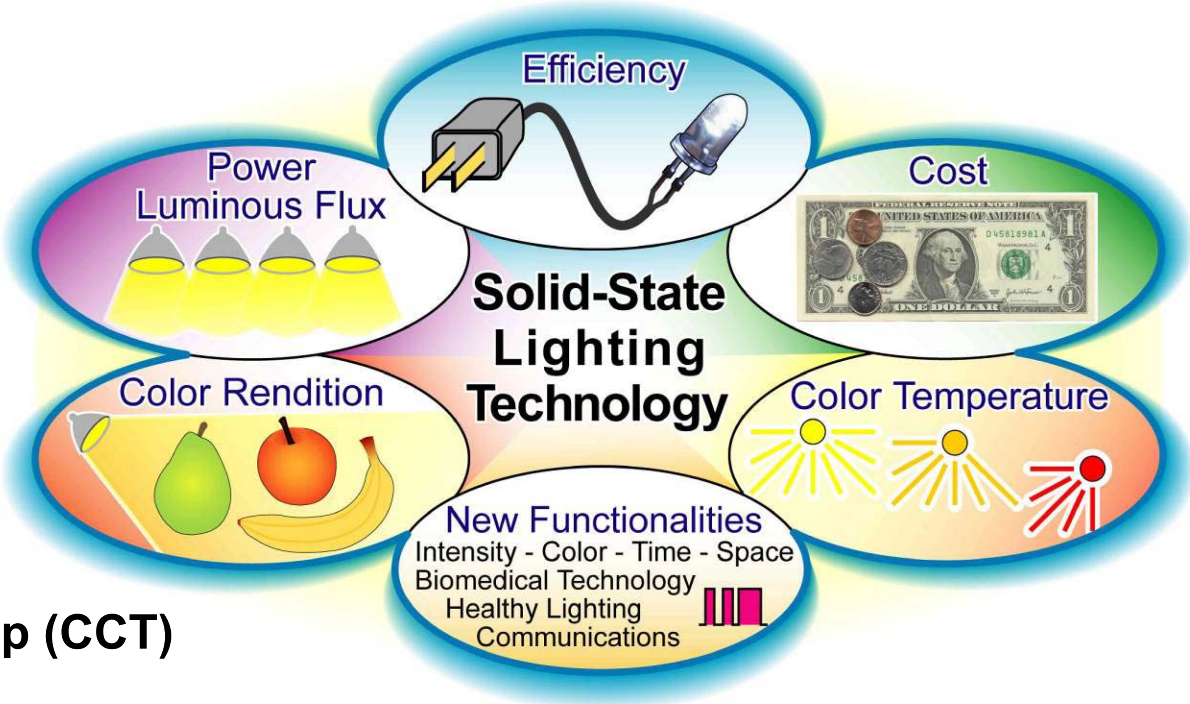


- **Assuming major government investments, by 2025 we expect to:**
  - **decrease electricity consumed by lighting by 50%**
  - **decrease total electricity consumption by 10%**

Projected Year 2025 Savings	US	World
Electricity used (TWh/yr)	620	~2,000
$ spent on Electricity ($B/yr)	42	~150
Electricity generating capacity (GW)	70	~250
Carbon emissions (MtC/yr)	100	~350

Other metrics for SSL performance

- Lamp power
- Cost
- Lifetime
- Directionality
- Operating temp
- Correlated Color Temp (CCT)
- Color Rendering Index (CRI)



Courtesy E.F. Schubert, RPI

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Efficiency and Cost of White Light Sources

Source efficacy – mean lumens (2006)

- Incandescent (60W) ~14 lpw
- Fluorescent (F32T8) ~83 lpw
- HID (400W Metal Halide) ~80 lpw
- SSL (White LED) ~45 lpw

Normalized retail lamp price (2006)

- Incandescent (60W) ~0.30 $/klm
- Fluorescent (T8) ~0.60 $/klm
- HID (Metal Halide) ~2.00 $/klm
- SSL (White LED) ~64.00 $/klm (250 $/klm in 2005)

Research is improving SSL efficacy while decreasing price

Source: Solid-State Lighting Research and Development Portfolio, Multi-Year Program Plan FY'07-FY'12, March 2006

What is the theoretical maximum luminous efficacy for SSL?

Must specify several properties of the white light to answer this question.

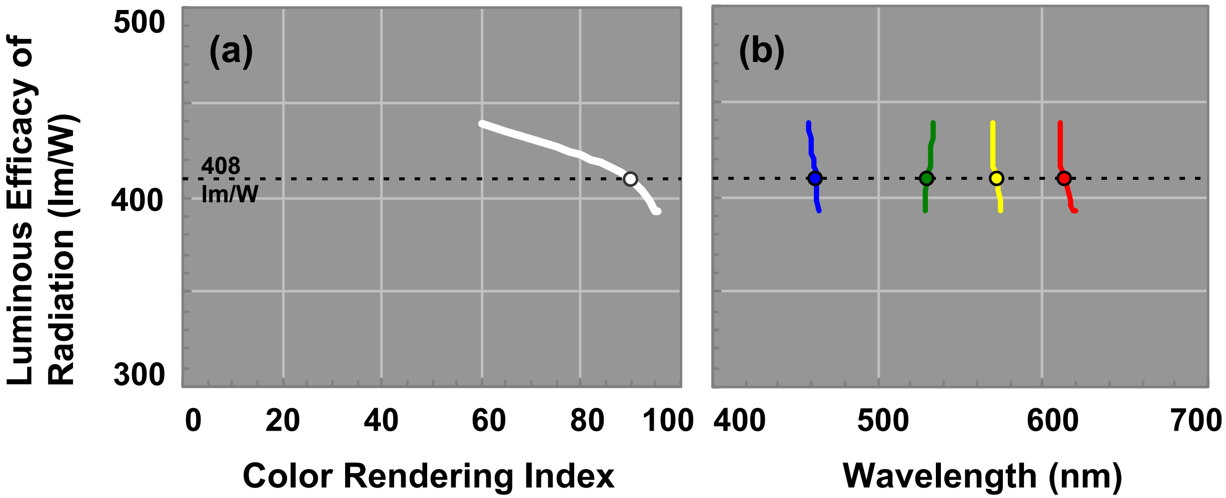
- Coordinated color temperature (CCT)
  - choose 3,000 K (corresponds to "warm white")
- Color rendering index (CRI)
  - choose $R_a = 90$; "excellent CRI" for all applications
  - trade-off between CRI and luminous efficacy (L.E.)
- Number of component color sources
  - more colors provide higher CRI (but lower L.E.)
  - n=5, R_a=99; n=4, R_a=97; n=3, R_a=85
- Linewidths of color sources
  - narrow linewidths give (slightly) better L.E. without a penalty in CRI
  - choose FWHM=1 nm

White-light simulator used to find optimum luminous efficacies

Spreadsheet-based calculator (Yoshi Ohno, NIST)

- **Inputs**: center wavelengths & linewidths of sources, CCT
- **Calculates**: spectral distributions of color components and the resulting CRI
- **Outputs**: power ratios of the colors to produce white light on the Planckian locus at input CCT; L.E. of radiation
- **Iteration**: find wavelengths that give maximum L.E. for a specified CRI
  - linewidths of semiconductor sources fixed (1 nm)
  - linewidths of phosphors varied to maximize L.E.

Maximum luminous efficacy as a function of CRI



- **Maximum L.E. drops with increasing CRI (expected result)**
- **408 lm/W is the maximum L.E. for 4-color SSL with CRI=90 (100% wall-plug efficiency of semiconductor sources)**
  - **463 nm (B), 530 nm (G), 573 nm (Y), 614 nm (R)**
  - **define: 408 lm/W = "100% efficient SSL"**
- **small differences in λ; larger variations in watt fractions**
  - **CRI 60: 15% (G), 33% (Y); CRI 90: 23% (G), 22% (Y)**

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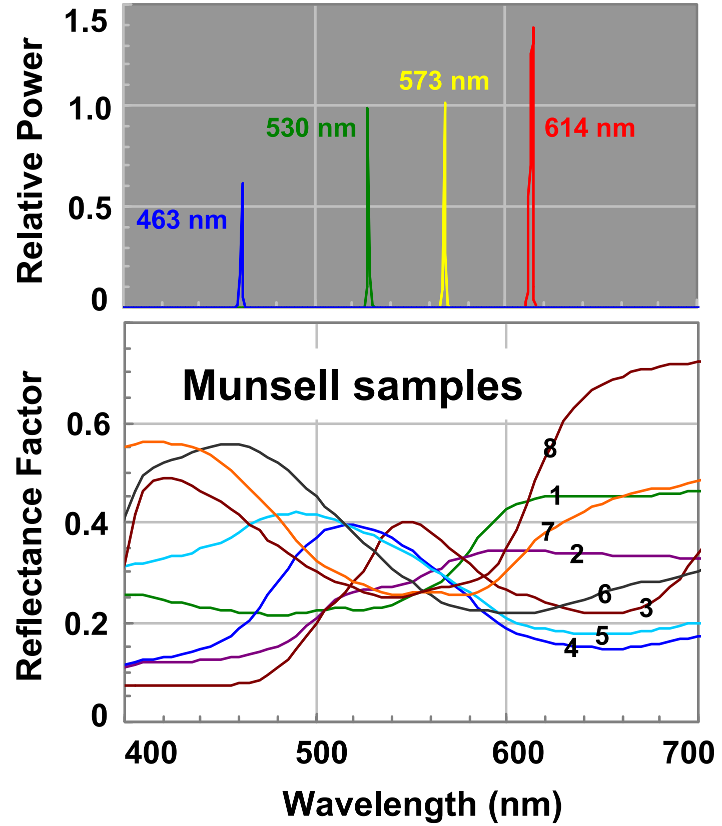
Characteristics of optimal 4-color light source

- Widely spaced across the visible wavelengths
- Relative watt fractions:
  - B: 14%, G: 23%; Y: 22%; R: 41%
- Why is red such a large fraction?
  - important for good CRI
  - far from peak eye responsivity
- Linewidths are very narrow compared to the broadly varying Munsell samples (basis of CRI)
  - 1 nm linewidths (or 20 nm linewidths characteristic of LEDs) are nearly "δ-functions"
  - explains insensitivity of CRI to source linewidth



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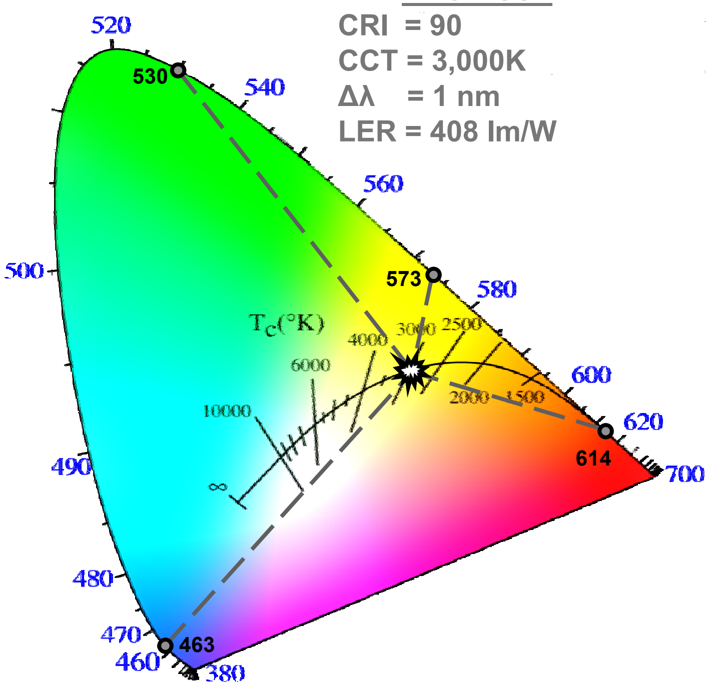
Three approaches to reaching "ultra-efficient" (> 70%) SSL



- Current long-range U.S. targets are for 50%-efficient SSL (204 lm/W)
- Global energy-consumption benefits would continue beyond current goal
- Is 70% efficiency (286 lm/W) possible?

- Three possible approaches:
  - **RYGB**: light mixed from 4 "primary semiconductor" sources
  - **RG_BB**: Green produced by secondary phosphor (pumped by blue)
  - **R_BG_BB**: Red & Green both produced by secondary phosphors (pumped by blue)

Each approach has distinct research challenges

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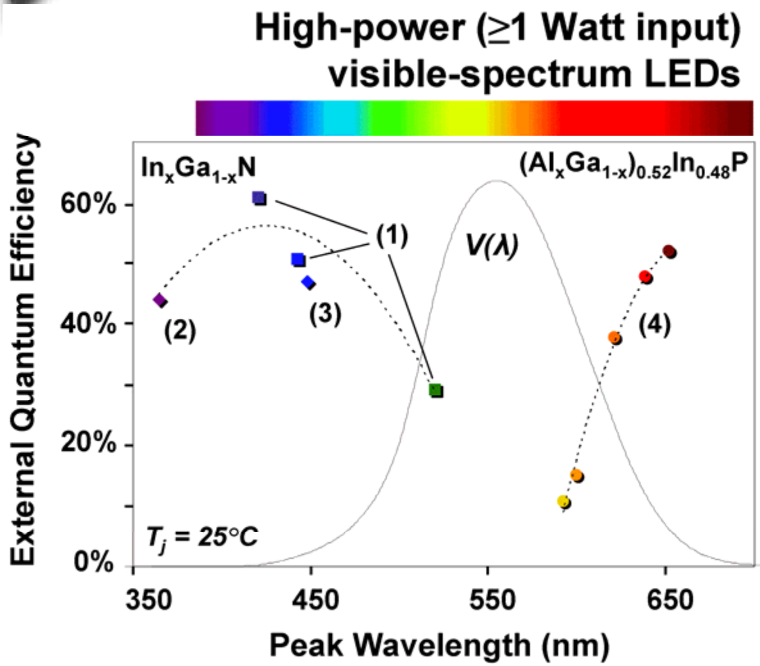
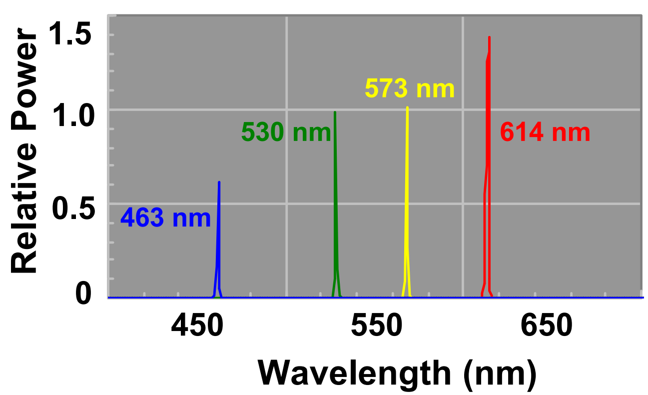
Technical challenges in the RYGB approach





- InGaN materials have direct band gaps over the entire visible range
  - potential of spanning blue to red
- Dramatic drop in InGaN efficiency with higher In-content (longer λ)
  - increased strain, producing large internal polarization fields, morphological / compositional instability, defects from low-T growth
- $(Al_xGa_{1-x})_{0.52}In_{0.48}P$ efficiency drops with higher Al-content (shorter λ)
  - band gap changes from direct to indirect ~x=0.55
- Result: the "green gap"

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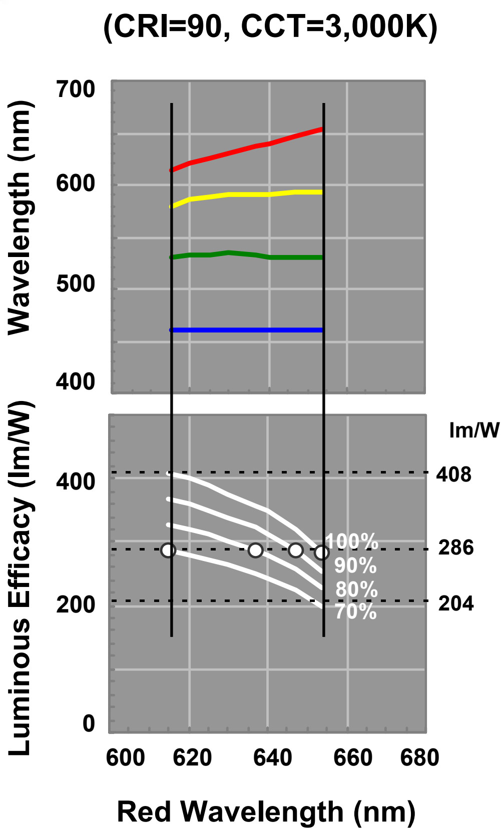
Technical challenges in the RYGB approach



- Red wavelength very important
  - shorter wavelength improves L.E.; closer to peak eye sensitivity (but CRI=90 is impossible for λ < 615 nm)
  - longer wavelength improves CRI (but L.E. > 286 lm/W impossible for λ > 654 nm)
- If 100%-efficient primary semicond. sources
  - 614 nm Red: 408 lm/W; 654 nm: 286 lm/W
- If 70%-efficient primary semicond. sources
  - 615 nm Red needed to reach 286 lm/W, but AlInGaP efficiency drops as λ get shorter
- How to get Blue, Green, Yellow at >70% efficiency?

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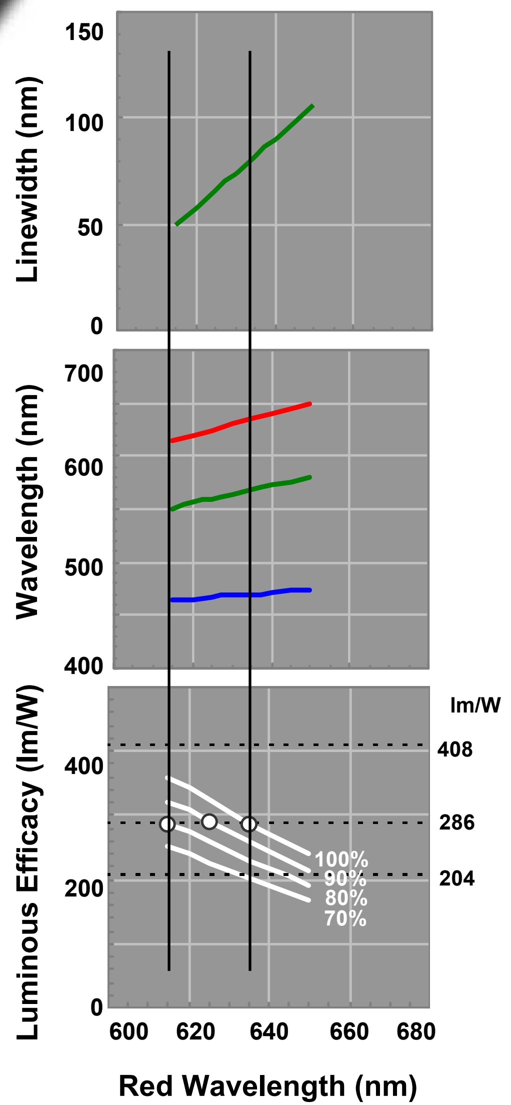
Technical challenges in the RG_BB approach



- Red, blue primary semiconductor sources; green phosphor pumped by blue
- 95% efficiency assumed for green phosphor (less the 15.4% Stokes loss)
  – very challenging goal
- Narrower range of red wavelengths
- Efficiencies of 80% (615 nm red) or 90% (626 nm red) needed to reach 286 lm/W
- Broad linewidths needed for green phosphor (50-75 nm) as red λ increases
  – improves CRI to make-up for "missing" short-λ red
- Why only 3 colors (instead of 4)?
  – broad green phosphor replaces G,Y LEDs

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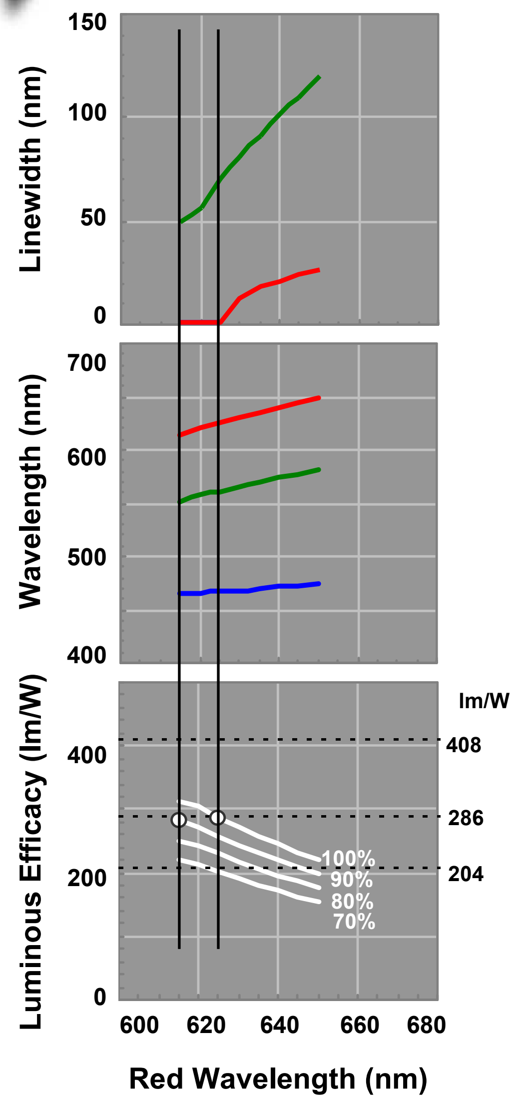
Technical challenges in the $R_B G_B B$ approach



- **Blue primary semiconductor source; green and red phosphors pumped by blue**
- **95% efficiency assumed for both phosphors**
  - **Stokes losses: 24.2% (red), 15.4% (green)**
- **Very narrow range of red wavelengths are allowed for > 286 lm/W**
- **Efficiencies of 90% (615 nm red) or 100% (625 nm red) needed to reach 286 lm/W**
- **Broad linewidths needed for green phosphor (50-70 nm) as red λ increases**
- **Narrow linewidth (1 - 20 nm) needed for red phosphor pumped by blue**
  - **currently no phosphor system like this**

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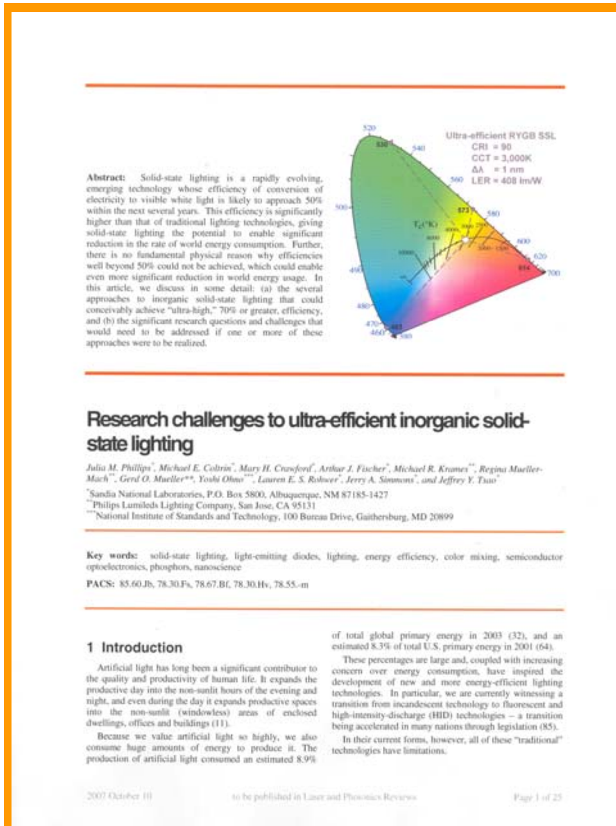
Research challenges to "ultra-efficient" SSL discussed in new review article

Summary: ***There is no fundamental physical reason why efficiencies well beyond 50% could not be achieved, which could enable even more significant reduction in world energy usage. In this article, we discuss: (a) several approaches to inorganic solid-state lighting that could conceivably achieve "ultra-high" (> 70%) efficiency, and (b) the significant research questions and challenges that need to be addressed realize this goal.***

Article to be published in :

J.M. Phillips, et al., Lasers & Photonics Reviews

(on-line version available soon)



Abstract: Solid-state lighting is a rapidly evolving, emerging technology whose efficiency of conversion of electricity to visible white light is likely to approach 50% within the next several years. This efficiency is significantly higher than that of traditional lighting technologies, giving solid-state lighting the potential to enable significant reduction in the rate of world energy consumption. Further, there is no fundamental physical reason why efficiencies well beyond 50% could not be achieved, which could enable even more significant reduction in world energy usage. In this article, we discuss in some detail: (a) the several approaches to inorganic solid-state lighting that could conceivably achieve "ultra-high," 70% or greater, efficiency, and (b) the significant research questions and challenges that would need to be addressed if one or more of these approaches were to be realized.

Research challenges to ultra-efficient inorganic solid-state lighting

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Key words: solid-state lighting, light-emitting diodes, lighting, energy efficiency, color mixing, semiconductor optoelectronics, phosphors, nanoscience

PACS: 85.60.Jb, 78.30.Fs, 78.67.Bf, 78.30.Hv, 78.55.-m

1 Introduction

Artificial light has long been a significant contributor to the quality and productivity of human life. It expands the productive day into the non-sunlit hours of the evening and night, and even during the day it expands productive spaces into the non-sunlit (windowless) areas of enclosed dwellings, offices and buildings (11).

Because we value artificial light so highly, we also consume huge amounts of energy to produce it. The production of artificial light consumed an estimated 8.9% of total global primary energy in 2003 (32), and an estimated 8.3% of total U.S. primary energy in 2001 (64).

These percentages are large and, coupled with increasing concern over energy consumption, have inspired the development of new and more energy-efficient lighting technologies. In particular, we are currently witnessing a transition from incandescent technology to fluorescent and high-intensity-discharge (HID) technologies – a transition being accelerated in many nations through legislation (85).

In their current forms, however, all of these "traditional" technologies have limitations.

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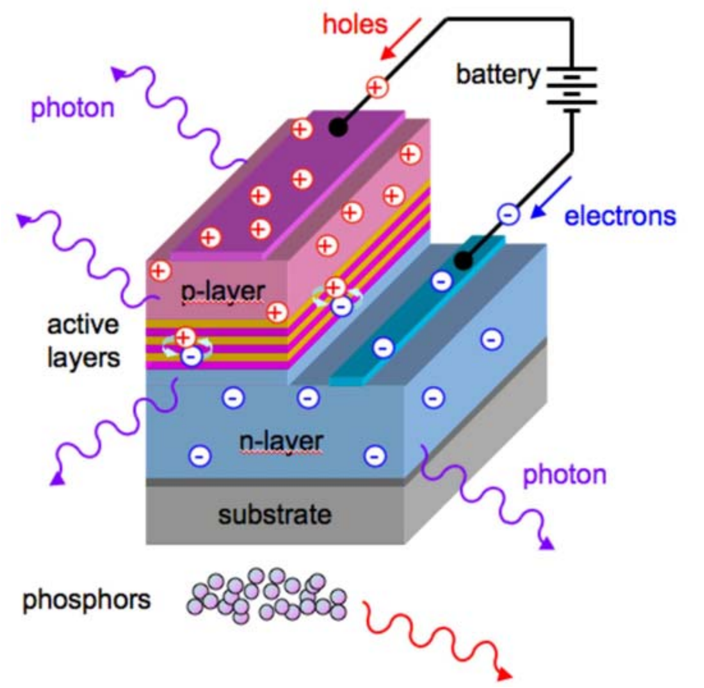
Five top-priority technological challenges for ultra-efficient SSL

- High internal radiative efficiency red semiconductor source in the 615 – 625 nm range
- High internal radiative efficiency green semiconductor source in the 530 – 570 nm range
- Efficient narrowband (< 20 nm) red phosphor pumped by blue
- High internal radiative efficiency (near 100%) blue semiconductor source in the 460 - 465 nm range
- High (> 90%) and directional light extraction techniques



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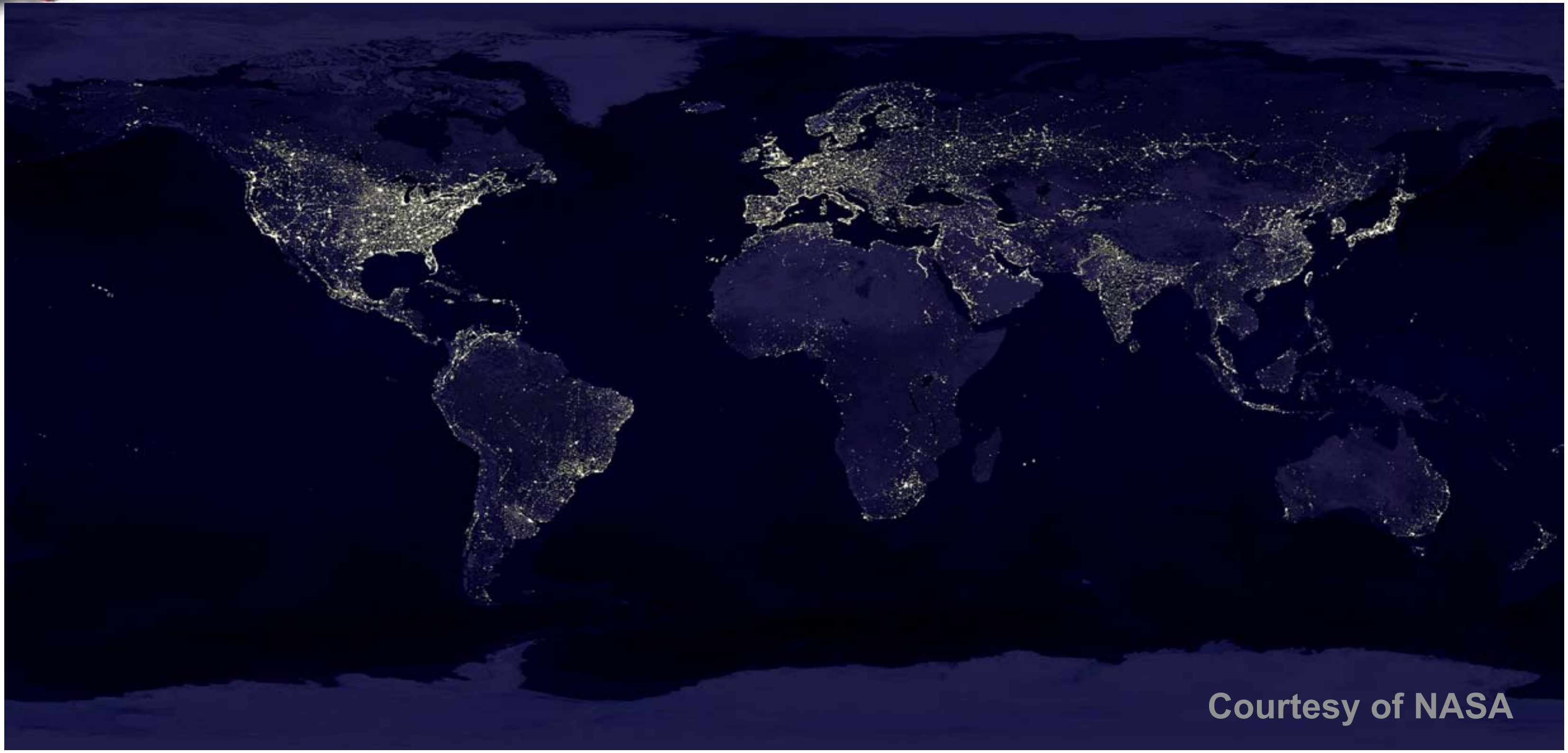
Dept. of Energy Workshop on
***Basic Research Needs** for Solid State Lighting*

***Workshop Charge:** To identify basic research needs and opportunities underlying light emitting diode and related technologies, with a focus on new or emerging science challenges with potential for significant long-term impact on energy-efficient and productivity-enhancing solid state lighting. Highlighted areas will include organic and inorganic materials and nanostructure physics and chemistry, photon manipulation, and cross-cutting science grand challenges.*

Full report available on the web:
http://www.sc.doe.gov/bes/reports/files/SSL_rpt.pdf

Summary



- 50% energy efficient Solid-State Lighting will replace all conventional lighting in ~20 years
- 70% efficiency may be feasible
- Significant investment in fundamental science as well as applied research & engineering is required to meet either goal
- Large, sustained, interdisciplinary investment is required

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