Solid-State Lighting:
An Opportunity for Nanotechnologists to Address the Energy Challenge

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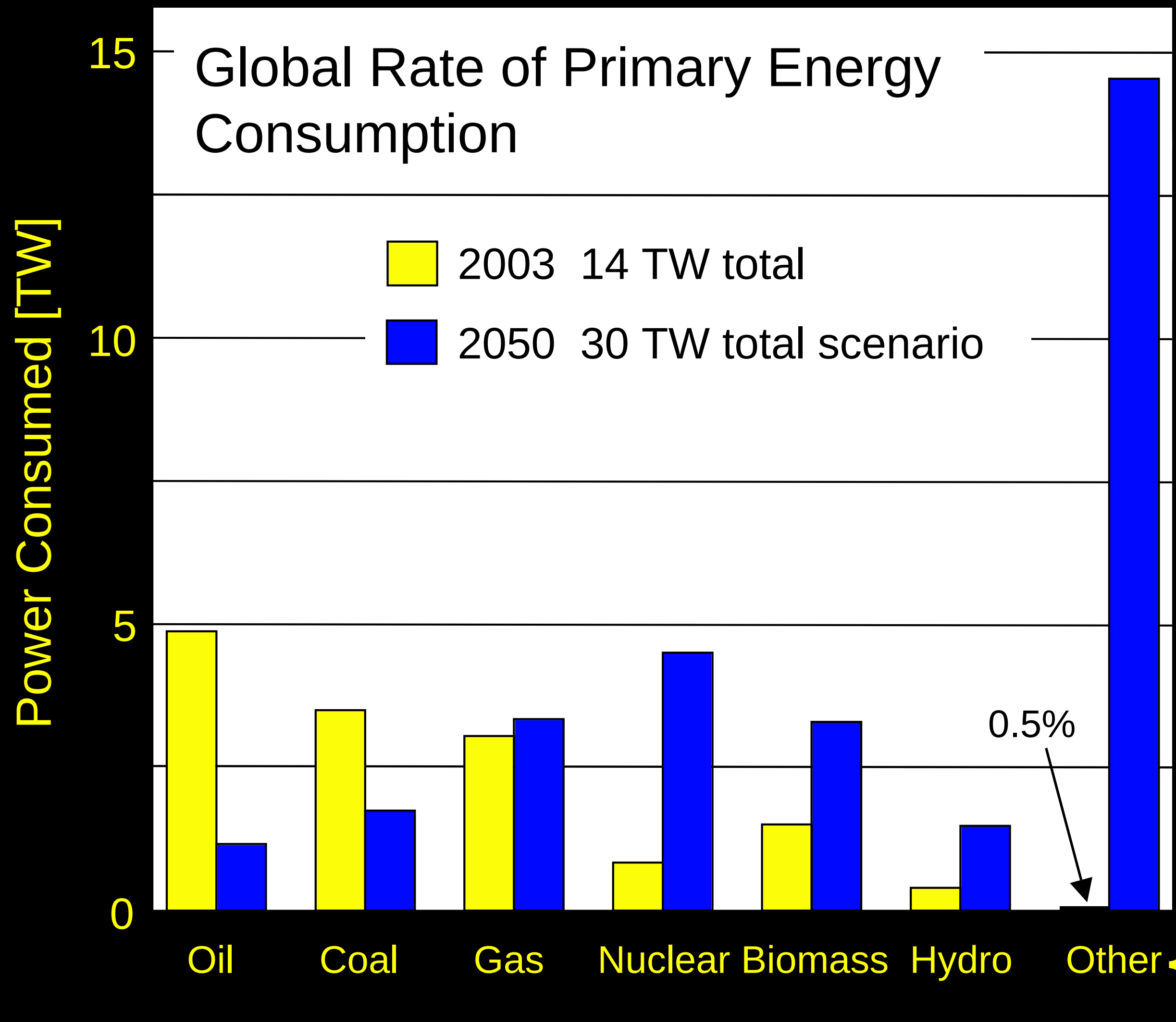
Outline

- The terawatt challenge
- Solid-state lighting - *the opportunity*
- Lighting - *a brief history*
- Lighting - *a tutorial*
- Light-emitting diodes
- Today's LED lighting technologies
- Challenges to meeting the SSL goal
- Potential nanotech solutions

The terawatt challenge



Primary source for 2003 data: International Energy Agency

Adapted from Richard Smalley's presentation on "Our Energy Challenge" at the 2004 International Electron Devices Meeting (IEDM), San Francisco, CA 12/14/04

Energy consumption rate *per capita*

- **In 2003:**
  - World: 2.24 kW/person (6.268 B people)
  - US: 10.4 kW/person (0.291 B people)
  - If everyone consumed at the US rate, the global rate of primary energy consumption would be ***65 TW***.
- **In 2050:**
  - The projection of 30 TW in 2050 corresponds to an average of 3 kW/person for 10B people…very conservative in light of the rapid changes in the developing world.

Rolling final report

By 2050, it is likely that….

- The population will grow from 6.5 B to 10 B
- The rate of global energy consumption will double
- CO_2 emissions will need to be reduced by a factor of two
- Oil production will decrease
- The use of nuclear energy will increase
- Solar, wind, and geothermal will increase dramatically
- ***Conservation*** will be an essential element of the solution

The solid-state part of the solution…

- More efficient devices for…
  - LED-based lighting
  - Thermoelectric refrigeration
  - Thermoelectric and thermophotovoltaic conversion of waste heat
  - Photovoltaic conversion of solar energy and production of hydrogen
- Added benefits
  - Compact
  - Robust
  - Low environmental impact
- Challenges
  - Efficiency breakthroughs needed!
  - Availability and price of raw materials
  - Manufacturing costs

The ^nano solid-state part of the solution…

- More efficient devices for…
  - LED-based lighting
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  - Compact
  - Robust
  - Low environmental impact
- Challenges
  - Efficiency breakthroughs needed! ***Nanostructured semiconductors?***
  - Availability and price of raw materials ***Thin films instead of bulk?***
  - Manufacturing costs ***"Bottom-up" nanofabrication?***

Solid-state lighting - *the opportunity*

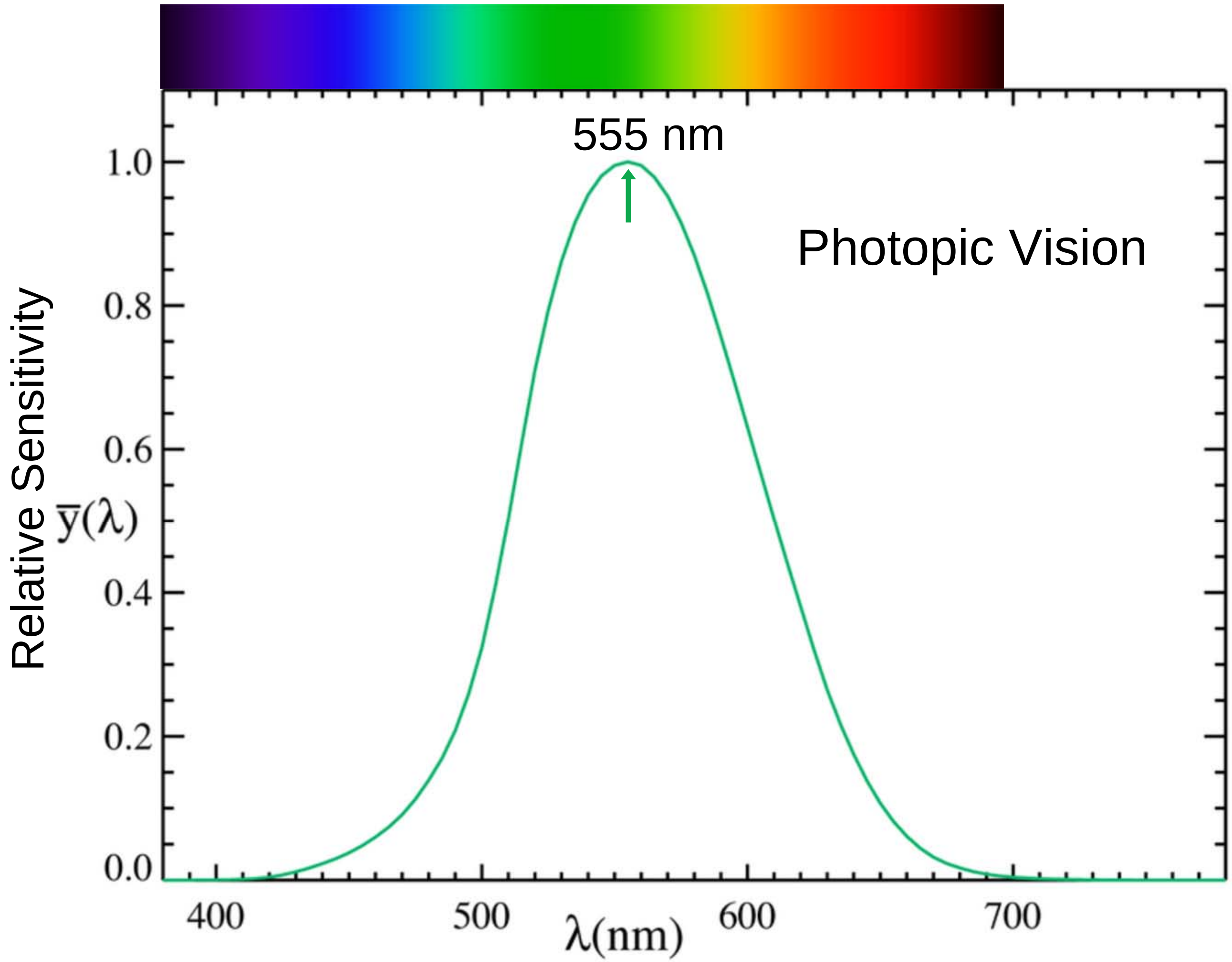
- Electricity generation accounts for about 37% of primary energy consumption in the U.S.*
- Lighting accounts for 22% of the nation's electric power usage.
- **The DoE Goal:** a solid-state lamp that is more efficient, longer lasting and cost competitive compared to conventional technologies, targeting a system efficiency of 50% and the color quality of sunlight.
- **Implications of Success:** 33% reduction in energy consumed for lighting by 2025, eliminating need for 41 1000MW power plants, and saving consumers \$128 B+.

+Navigant Consulting (11/03)
*Annual Energy Outlook (02)

Lighting - *a brief history*

- 1879 - first incandescent lamps by Joseph Swan and Thomas Edison
- 1901 - first low-pressure mercury vapor discharge lamp by Peter Cooper Hewitt (precursor of modern fluorescent lamps)
- 1932 - first commercial high-pressure mercury vapor lamp, a “high-intensity discharge lamp” (HID)
- 1961 - first patent for a metal-halide lamp (Gilbert Reiling)
- 1965 - first high-pressure sodium lamp
- 1996 - first commercial white LED (blue + phosphor)

Lighting - *a tutorial*



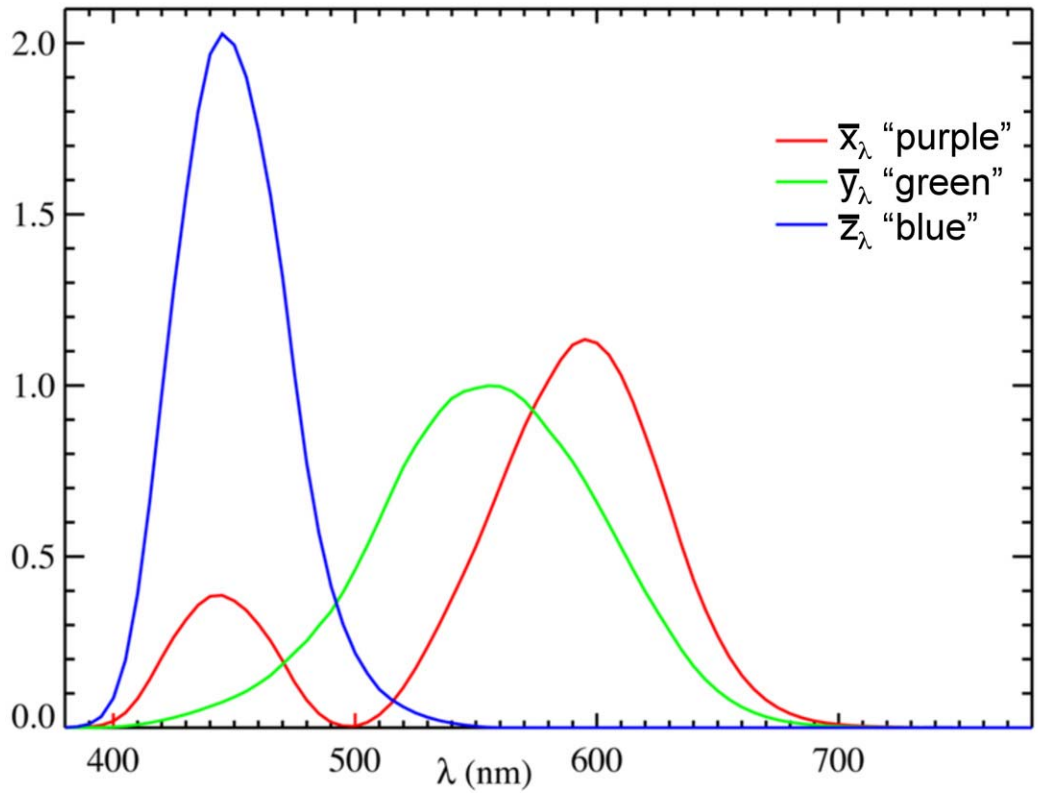
1931 CIE luminosity function (Wikipedia)

Definitions

- **Luminous Efficacy:** measure of ability of radiation to produce a visible sensation = luminous flux/radiant flux [lumen/$W_{radiant}$]
  - Radiant flux of 1W at λ = 555 nm produces luminous flux of 683 lumens
  - Any shift in λ or broadening of spectrum will reduce the luminous efficacy
- **Luminous Efficiency:** ability of source to convert consumed power into actuation of vision [lumen/W_{elec}] = (radiant flux/consumed power) · luminous efficacy

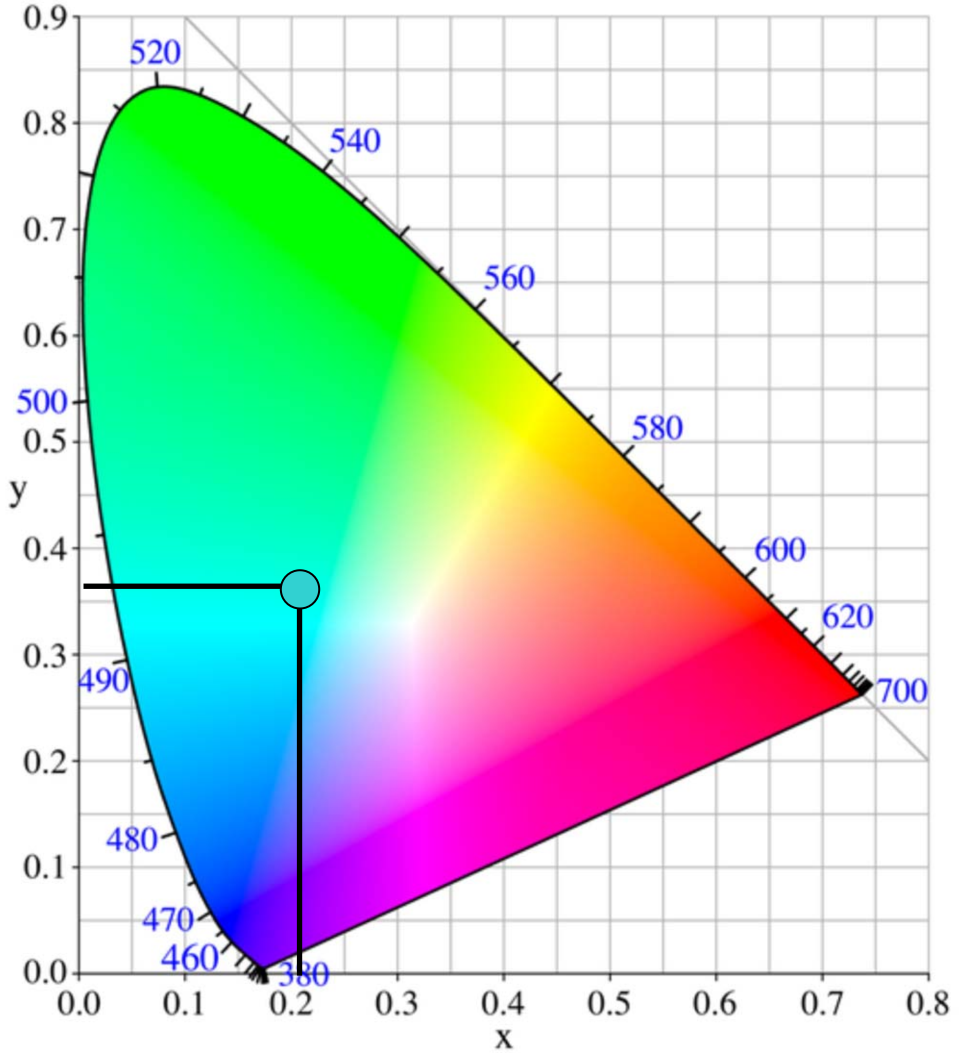
Color matching

- **Color Matching Functions:** construct spectrum of source by weighted sums of CMFs to arrive at **Chromaticity Coordinates (x,y)**



Chromaticity diagram

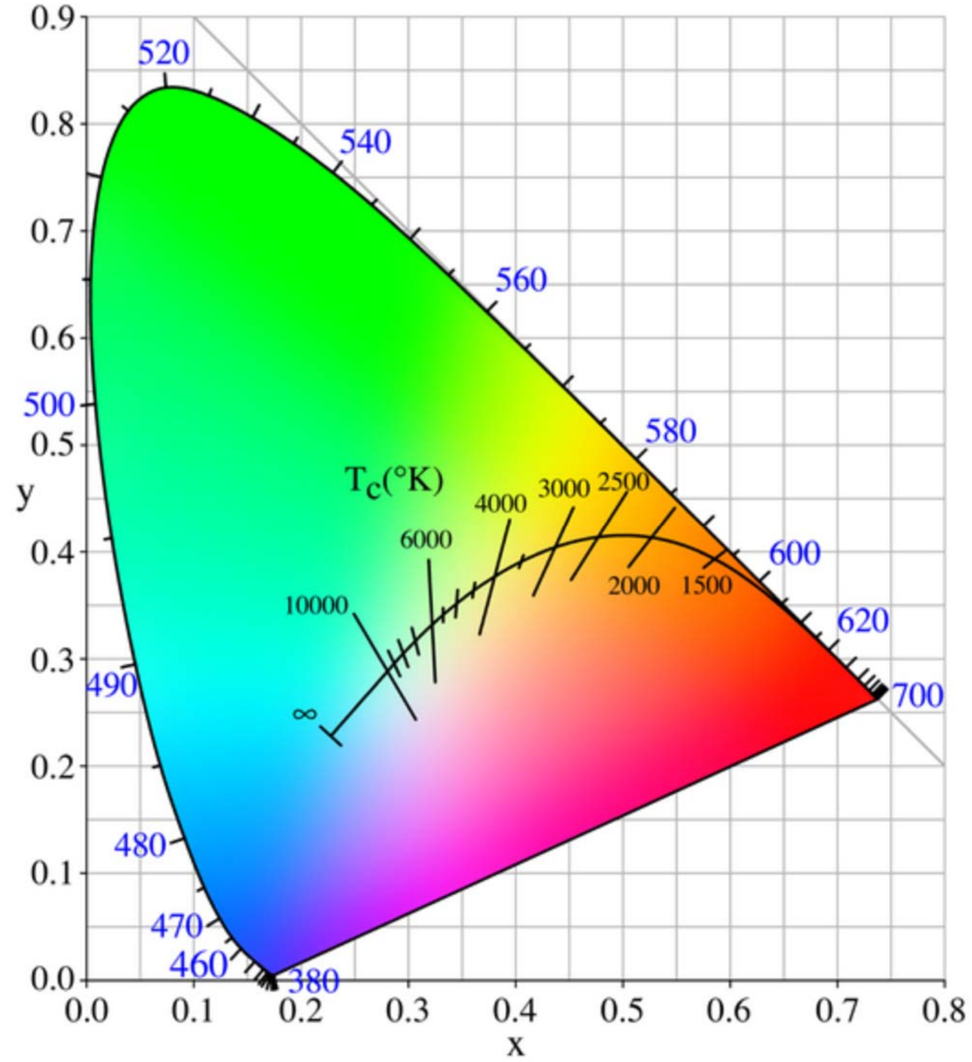
- Plot chromaticity coordinates (x,y) of source to yield perceived color
- Pure (monochromatic) colors on the perimeter



International Commission on Illumination - abbreviated as CIE from its French title Commission Internationale de l'Eclairage

Planckian Locus

- **Planckian Locus** describes black body color temperature [K].



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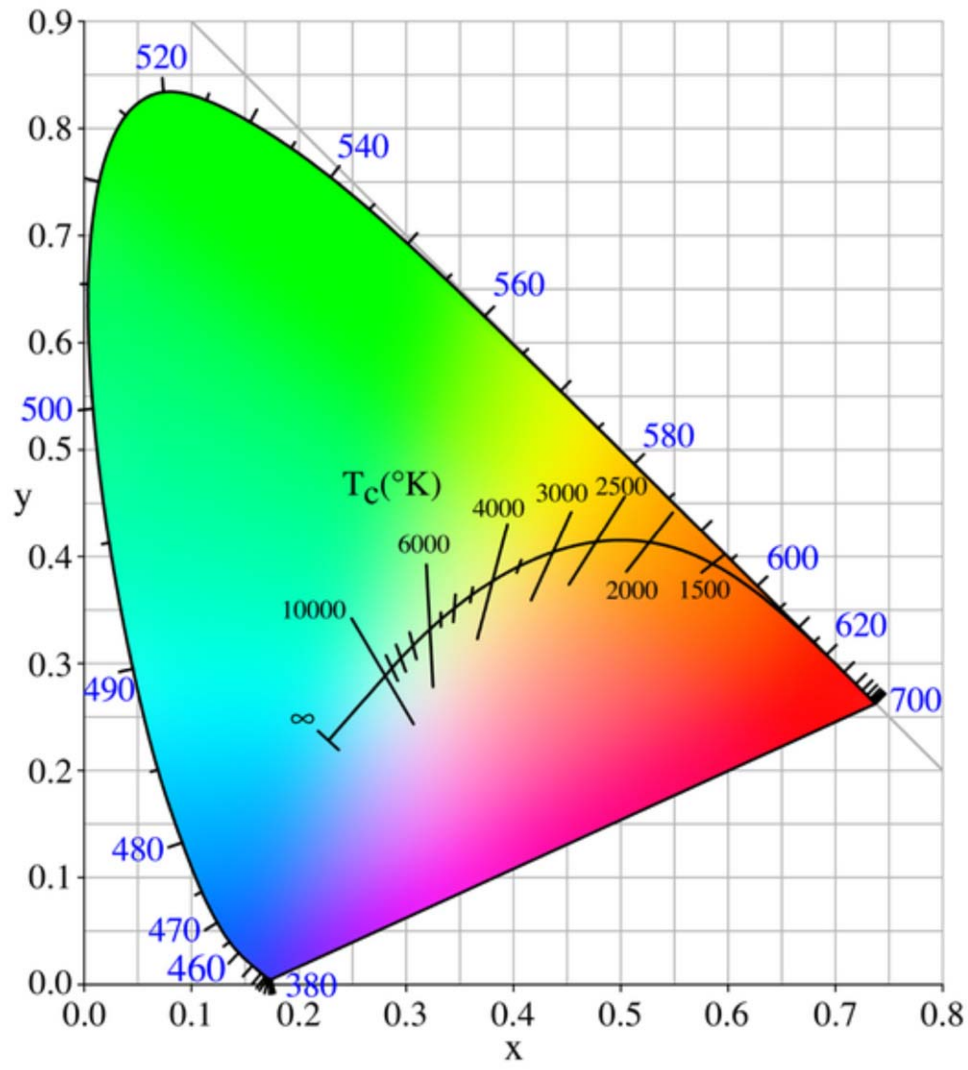
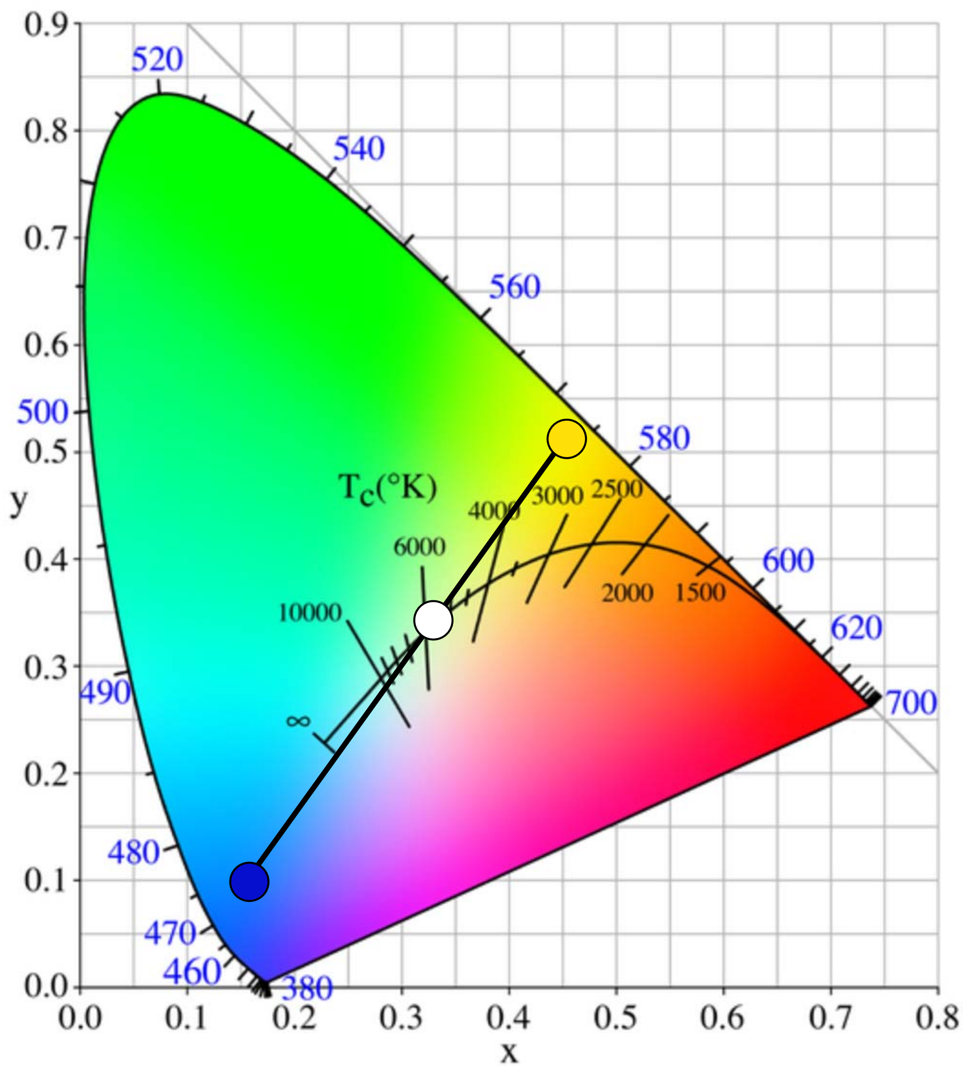
Standard Sources

- A: Tungsten at 2856K
- B: Direct sunlight - 4870K
- C: Overcast sunlight - 6770K
- D_{65}: Daylight - 6504K
- E: Point of equal energy (x,y) = (0.33,0.33)



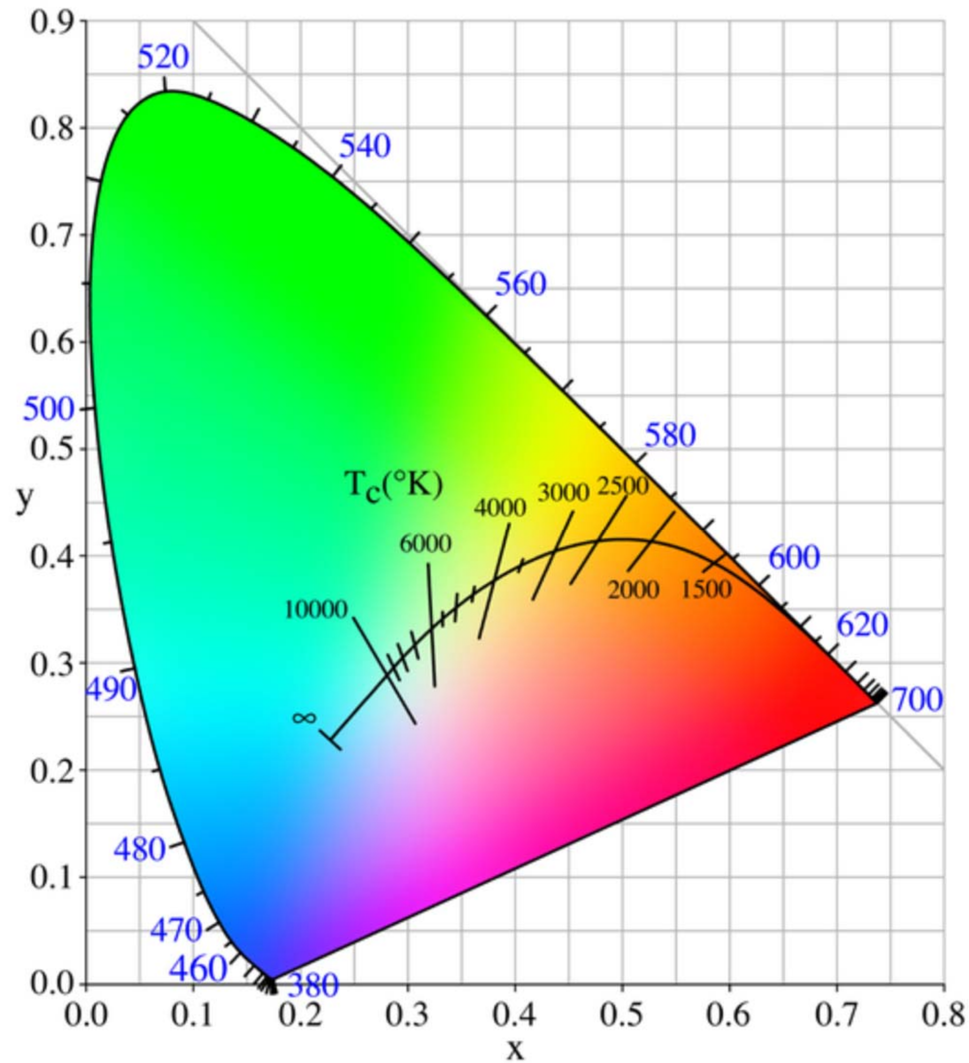
Color Rendering

- A blue + yellow source, properly weighted, is perceived as white, but will not satisfactorily render color upon reflection
- The color quality is defined by the **Color Rendering Index (CRI)**, defined as 100 for sunlight



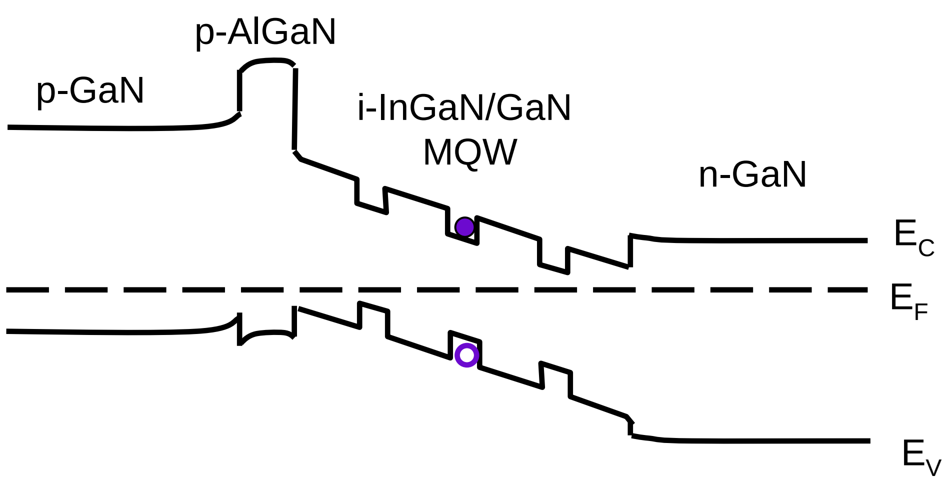
Desired characteristics

- luminous efficiency > 160 lumens/W
- System efficiency > 50%
- Color coordinates on the Planckian locus with color temperature between 3000K and 6000K
- CRI >85
- Lifetime > 50,000 h
- Lifecycle cost less than a few $/million lumen-hours



Light-Emitting Diodes (LEDs)

- Semiconductor p-n junction under forward bias
- Injected holes, electrons or both annihilate to generate a photon (radiative recombination)
- Wavelength determined by bandgap of the active region
- Monochromatic - ideal for traffic lights and safety signage



Typical band diagram at zero bias for a visible nitride LED

LED efficiency

$$\eta_{wall\text{-}plug} = \eta_{feeding} \cdot \underbrace{\eta_{injection} \cdot \eta_{IQE} \cdot \eta_{optical}}_{\eta_{EQE}}$$

Feeding efficiency: mean energy of photon emitted/qV_f.

Injection efficiency: fraction of electrons passing through diode that are injected into the active region.

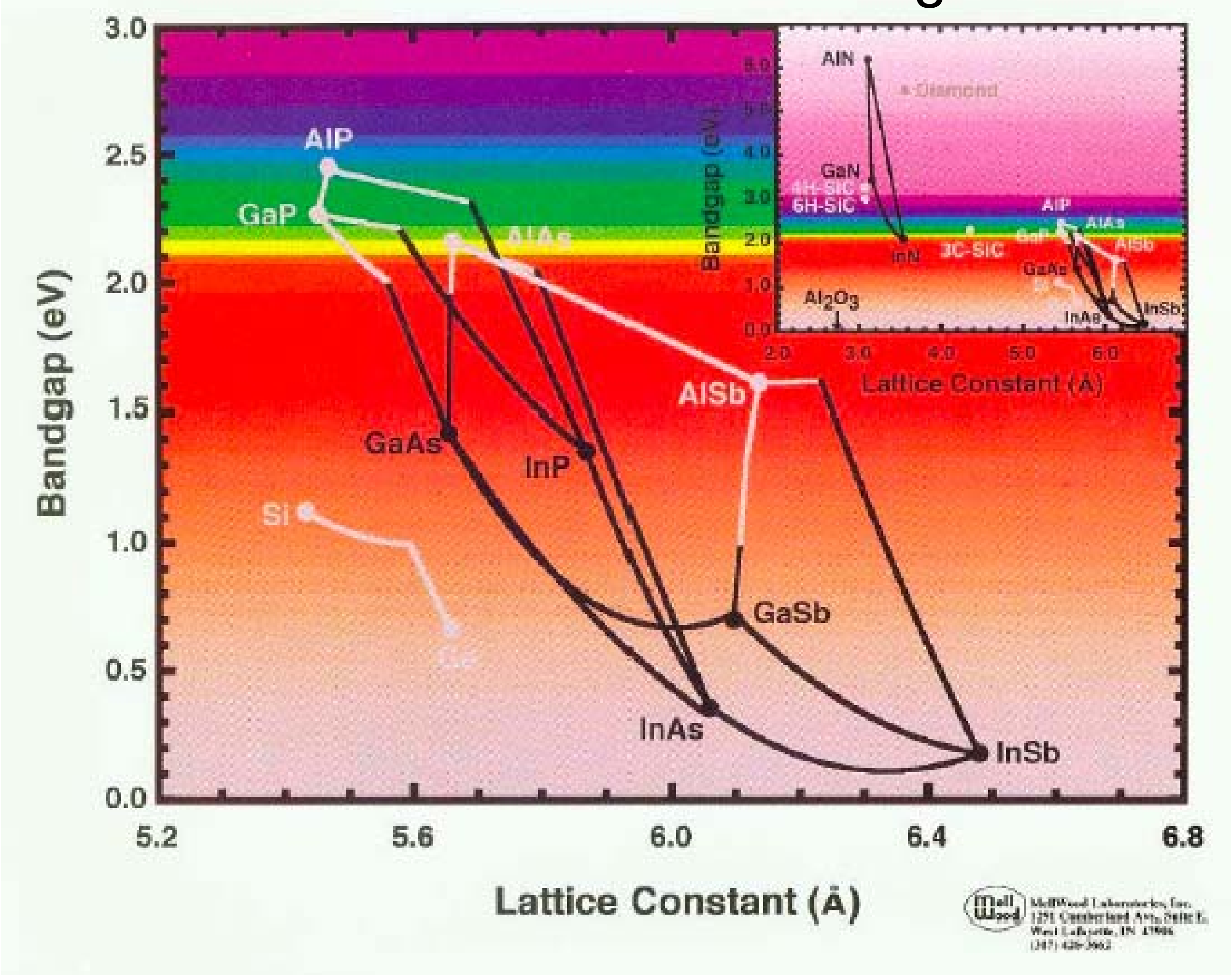
Internal quantum efficiency (IQE): fraction of e-h pairs recombining in active region that recombine radiatively.

Optical extraction efficiency: fraction of photons generated that escape from the device.

External quantum efficiency (EQE): number of photons emitted/number of electrons passing through diode

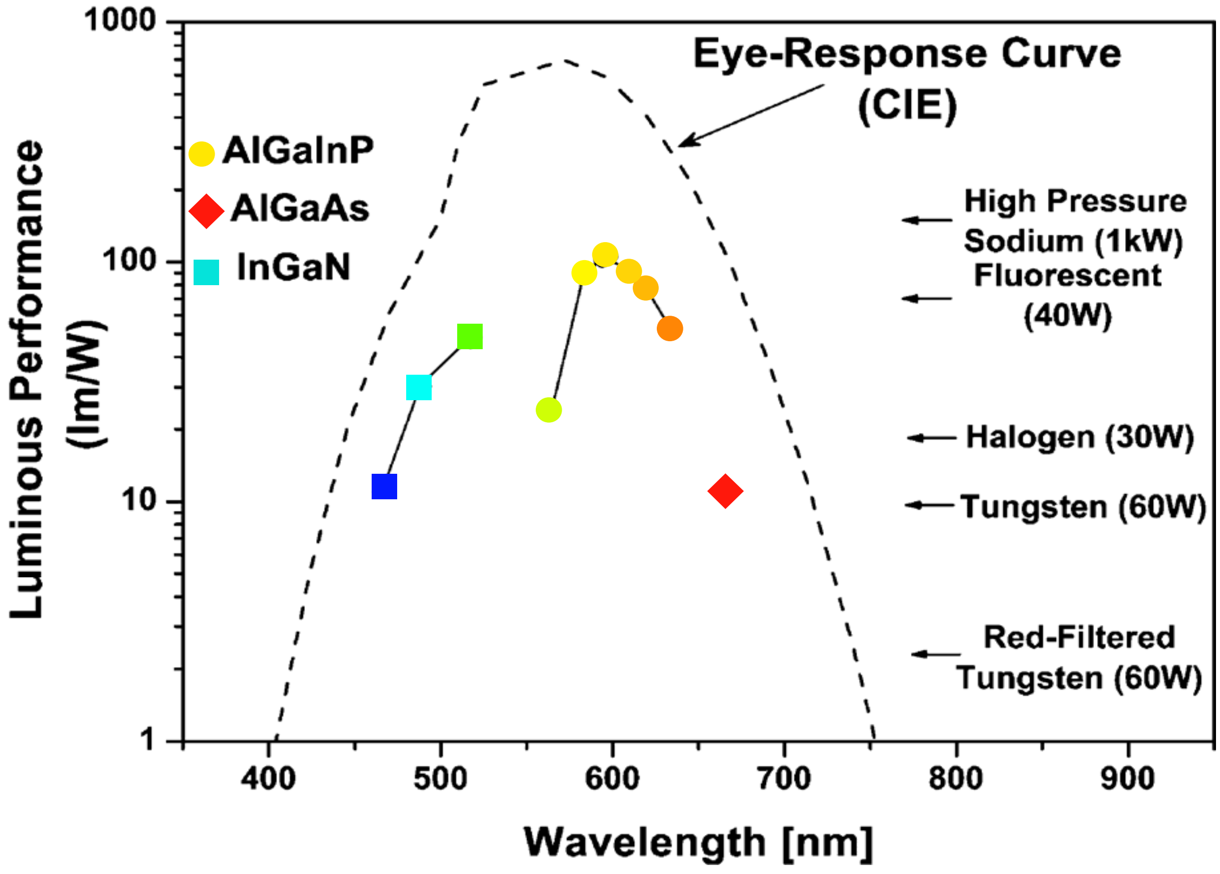
Bandgap vs. lattice constant

- **Desired:** a vertical black line traversing the visible spectrum



LEDs across the visible

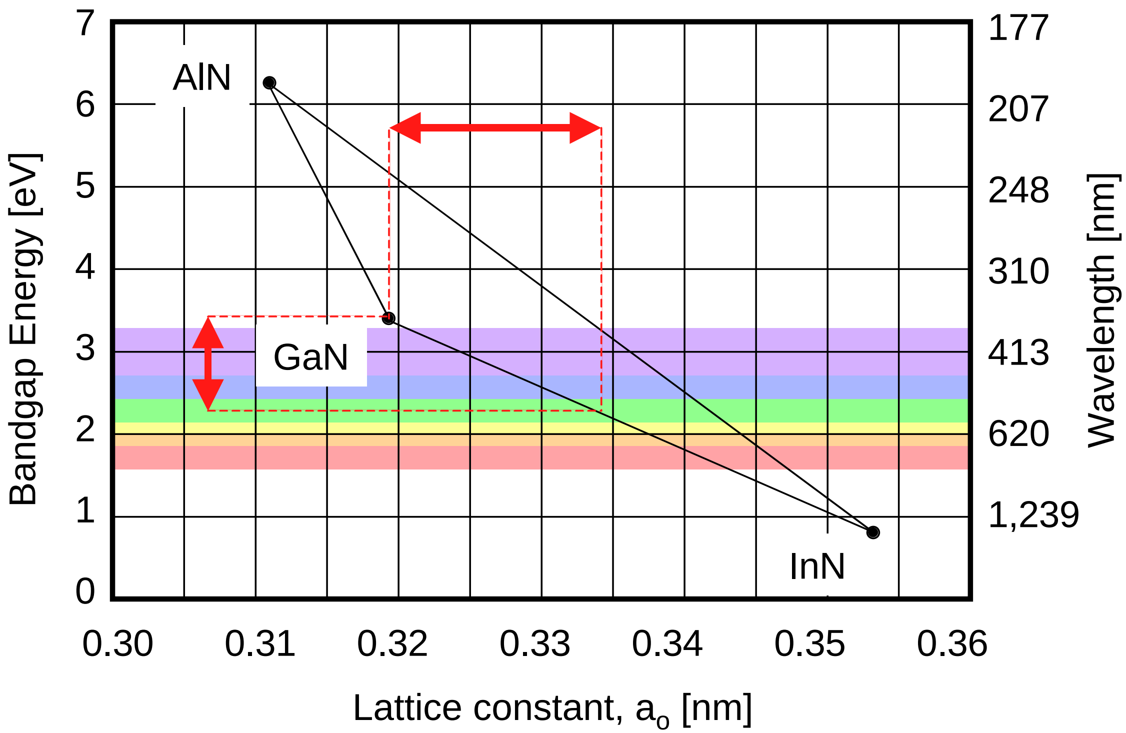
- III-V LEDs cover the visible spectrum, but not with one materials system



After Craford, MRS Bulletin, 2000

Why not full-spectrum emission from (In,Ga)N?

- Extended defects resulting from strain/miscibility gap act as nonradiative recombination sites
- Critical thickness of (In,Ga)N/GaN limited to a few nm for compositions that emit is the visible
- (In,Ga)N quantum well/quantum dot LEDs efficient in blue and green only



Efficiency trends

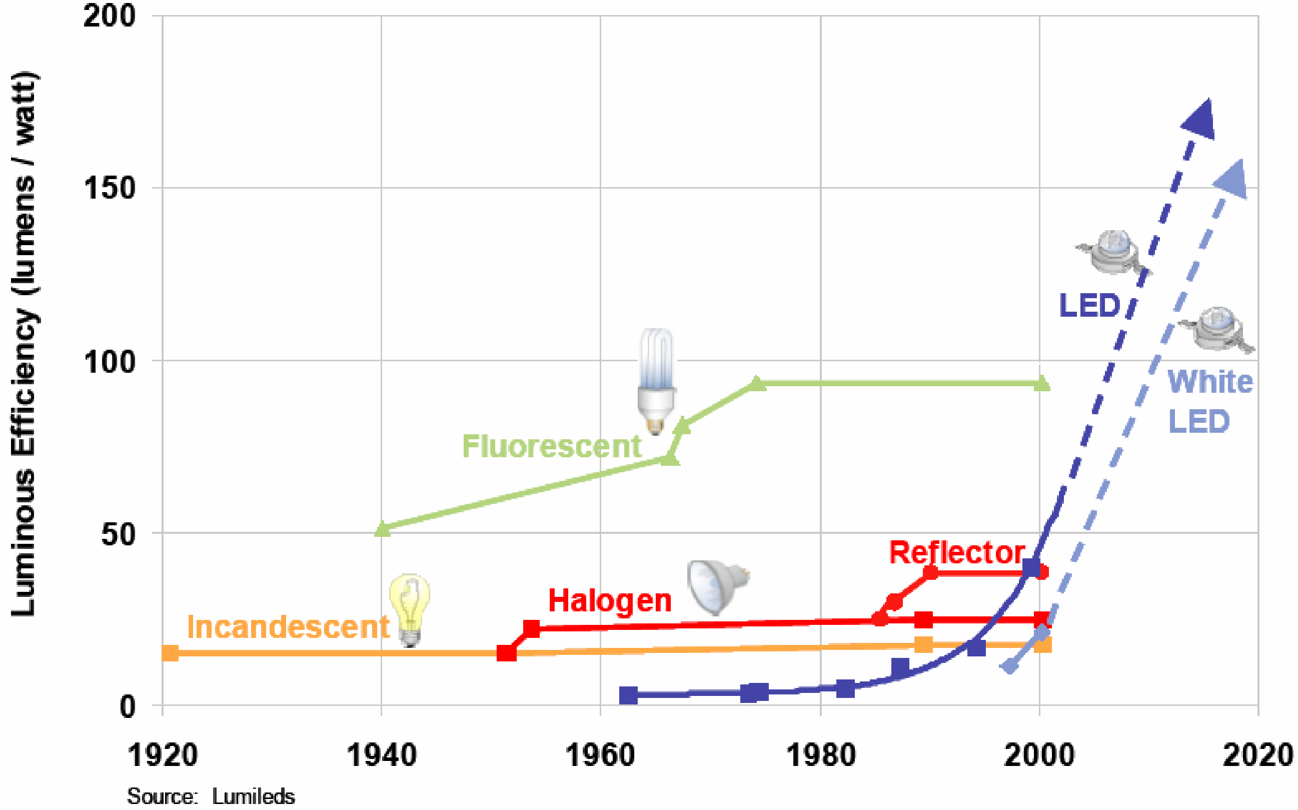


Figure 2-1: Historical and Predicted Efficacy of Light Sources

Source: Lumileds.

"Solid-State Lighting Research and Development Portfolio - Multi-Year Program Plan FY'07-FY'12, "prepared for DoE by Navigant Consulting, March 2006

Performance comparison (2005)

Table 2-1: Typical Performance of LED Devices and Conventional Technologies

Color	Luminous Output	Wattage	Luminous Efficacy	CCT (Typical)/ Dominant Wavelength	CRI	Lifetime
White	45 lm	1W	45 lm/W	5500°K	70	50k hours
Warm White	20 lm	1W	20 lm/W	3300°K	90	50k hours
Green	53 lm	1W	53 lm/W	530 nm	N/A	50k hours
Blue	16 lm	1W	16 lm/W	470 nm	N/A	50k hours
Red	42 lm	1W	42 lm/W	625 nm	N/A	50k hours
Amber	42 lm	1W	42 lm/W	590 nm	N/A	50k hours
Incandescent	850 lm	60W	14 lm/W	3300°K	100	1k hours
Fluorescent	5300 lm	32W	83 lm/W	4100°K	78	20k hours
HID	24,000 lm	400W	80 lm/W	4000°K	65	24k hours

Notes: For LED devices - drive current = 350ma, 1W device, T_j=25°C, batwing distribution, lifetime measured at 70% lumen maintenance. Lumen output is measure in mean lumens.
Source: Lumileds, 2005. GE, 2005. Philips Lighting, 2005. OSRAM Sylvania, 2005. Product Catalogs.

"Solid-State Lighting Research and Development Portfolio - Multi-Year Program Plan FY'07-FY'12, "prepared for DoE by Navigant Consulting, March 2006

Haitz's Law

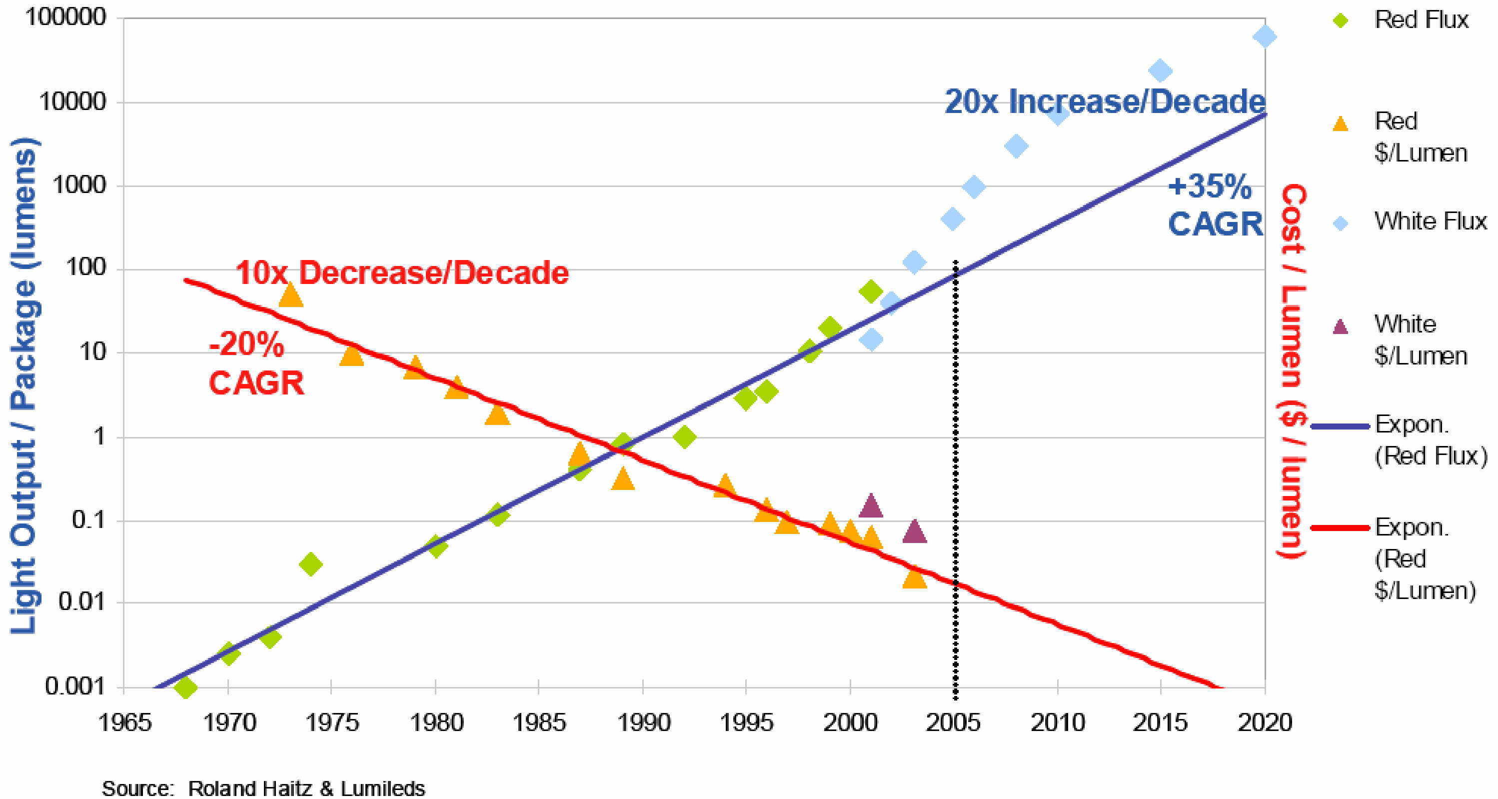


Figure 2-4: Haitz's Law: LED Light Output Increasing / Cost Decreasing

Source: Roland Haitz and Lumileds.
Note: CAGR = compound annual growth rate. Both lines are on the same numerical scale (however, different units)

"Solid-State Lighting Research and Development Portfolio - Multi-Year Program Plan FY'07-FY'12, "prepared for DoE by Navigant Consulting, March 2006

True cost of light

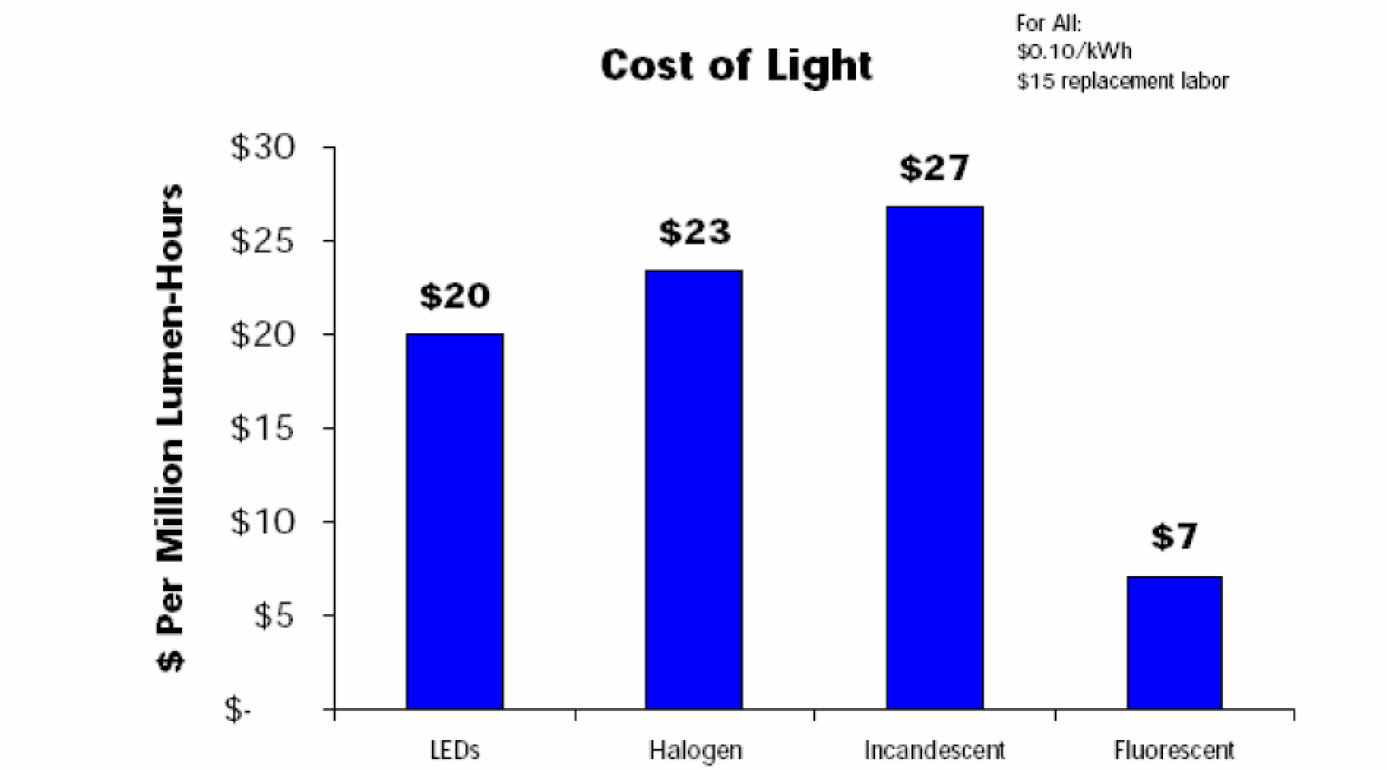


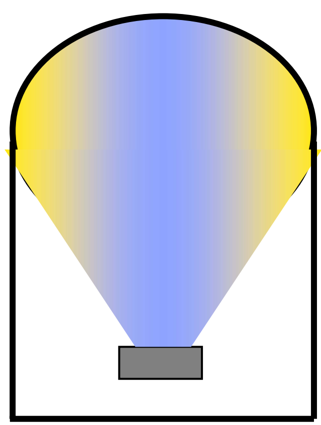
Figure 2-5: Cost of Light

Note/Source: To see how these values were calculated, please see the complete paper: "Cost of Light – When does Solid-state Lighting make Cents?" by Kevin Dowling, Color Kinetics, September 12, 2003.

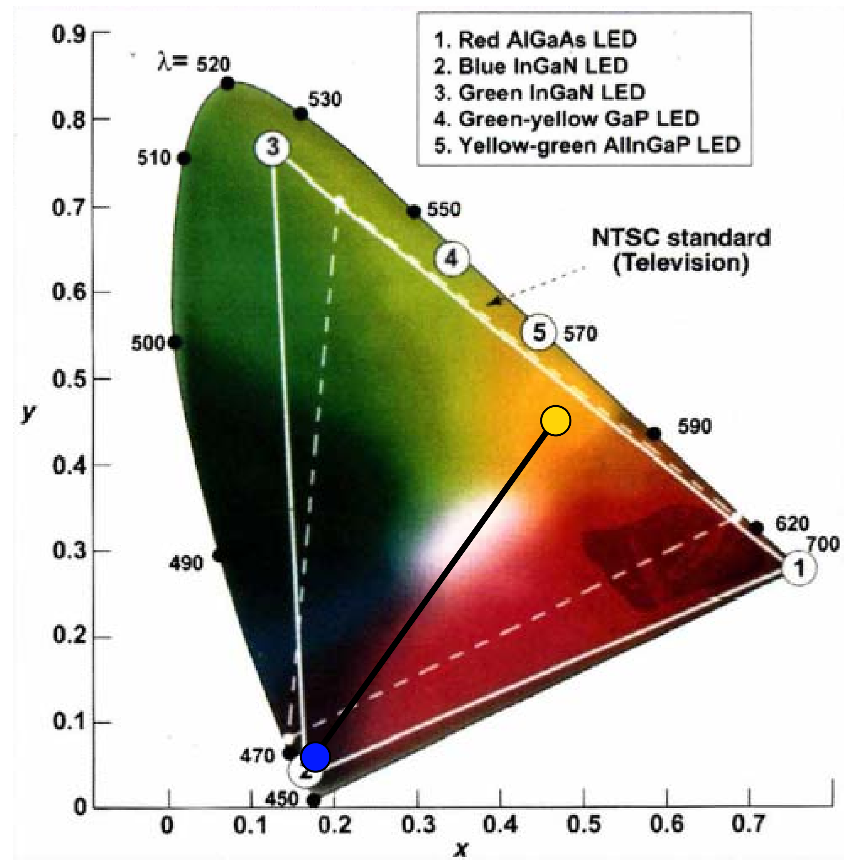
"Solid-State Lighting Research and Development Portfolio - Multi-Year Program Plan FY'07-FY'12, "prepared for DoE by Navigant Consulting, March 2006

SSL approaches: *blue GaN LED + phosphor*

- blue GaN LED with yellow phosphor embedded in epoxy dome



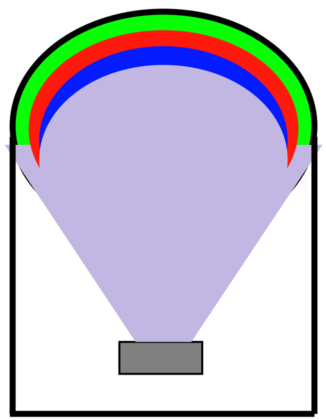
- *Low cost, but poor Color Rendering Index (CRI)*



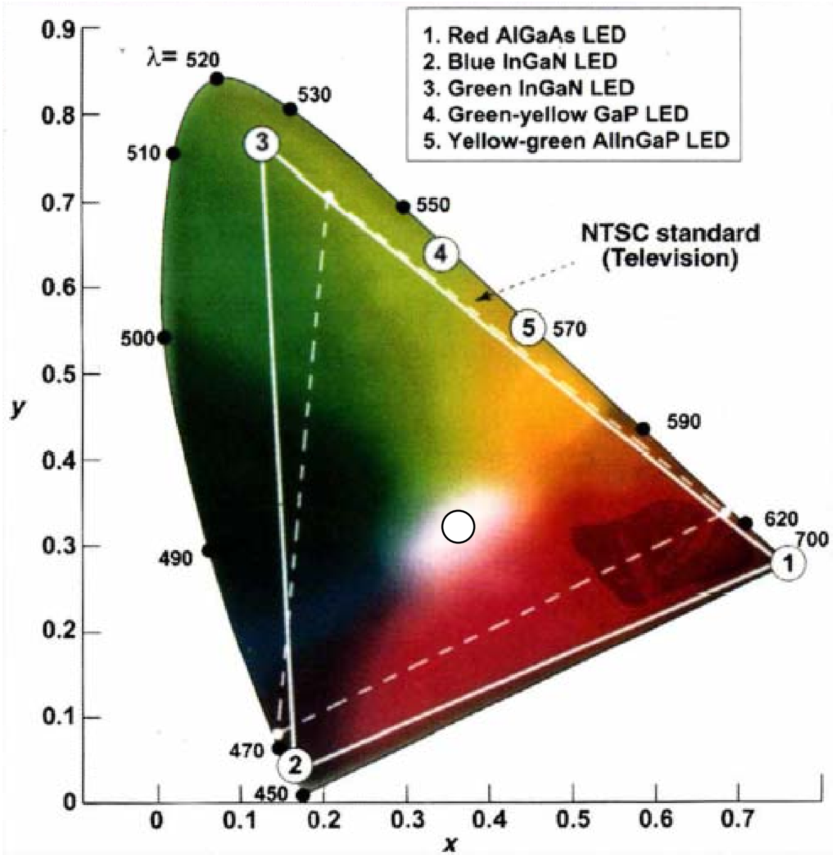
Chromaticity Diagram (CIE 1931)
Nitride-based Semiconductors for Blue and Green Light-emitting devices, FA Ponce and DP Bour, Nature 386 (1997) 351-9

SSL approaches: *uv GaN LED + phosphors*

- uv GaN LED with multiple phosphors embedded in epoxy dome



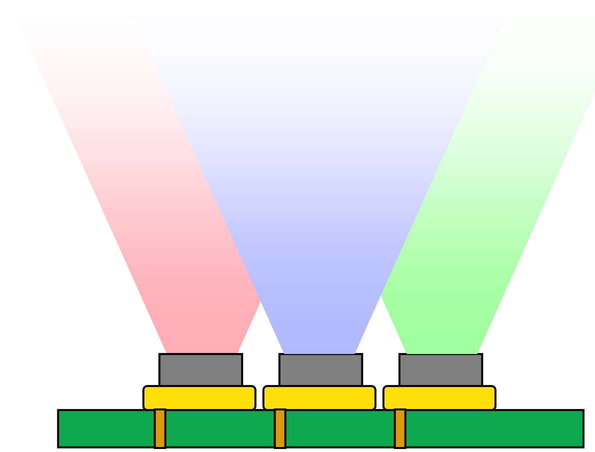
- *High CRI, but inefficient red phosphor, down-conversion losses and lamp lifetime concerns*

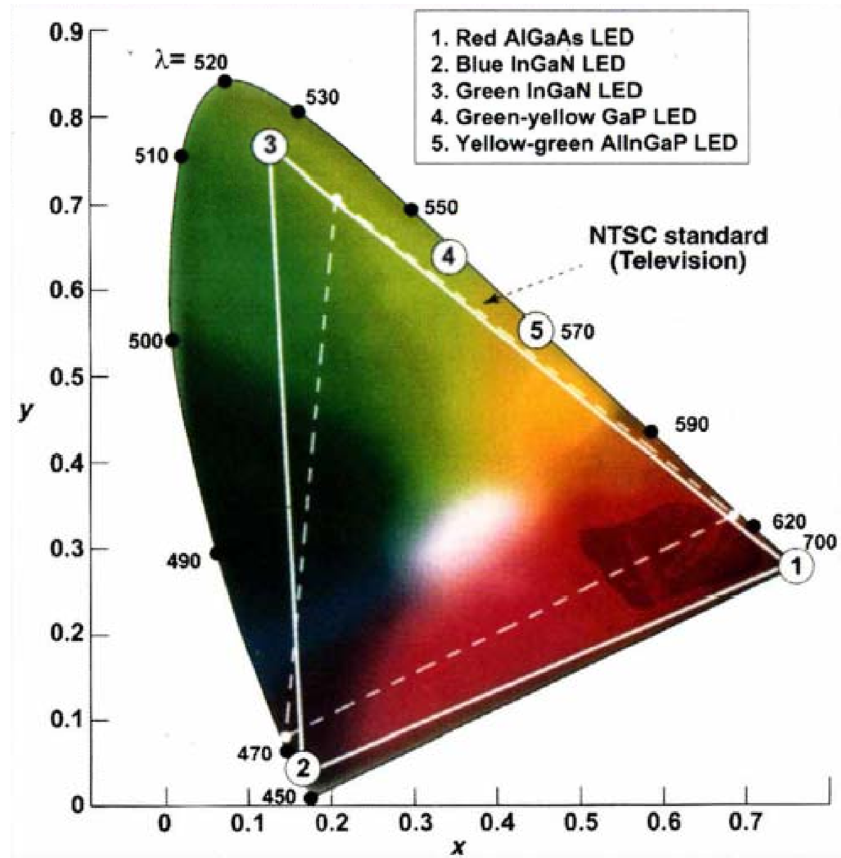


Nitride-based Semiconductors for Blue and Green Light-emitting devices, FA Ponce and DP Bour, Nature 386 (1997) 351-9

SSL approaches: *multichip*

- Integration of (Al,Ga,In)N (blue and green) with (Al,Ga,In)(As,P) (red) at the breadboard level





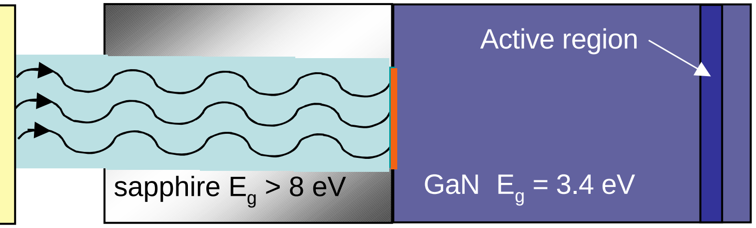
- *Great for large area displays…too expensive for general illumination!*

Nitride-based Semiconductors for Blue and Green Light-emitting devices, FA Ponce and DP Bour, Nature 386 (1997) 351-9

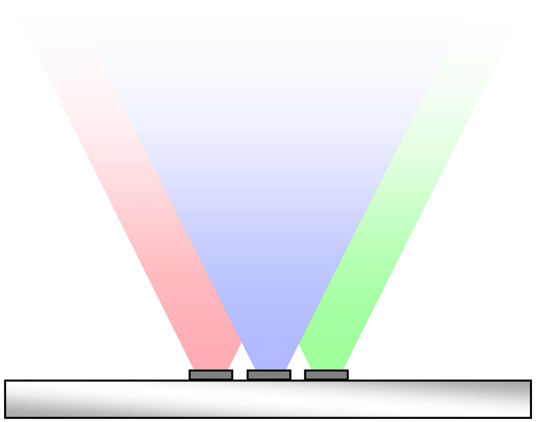
SSL approaches: *microdie transfer*

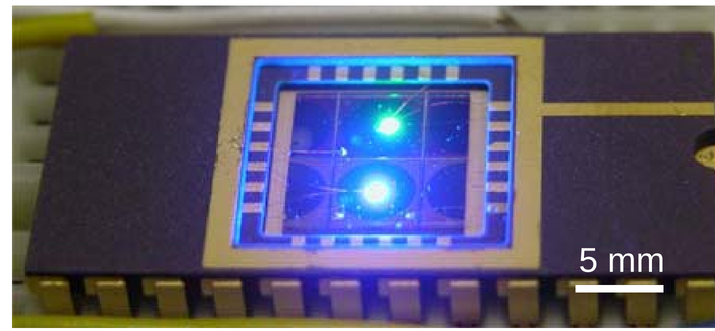
Laser Lift-off for transfer of GaN heterostructures from sapphire to Si or metal submount

Pulsed KrF excimer laser
Homogenized
Wavelength: 248 nm (5 eV)
Pulse duration: 30 ns
Fluence: 0.6 J/cm^2



- Integration at the wafer level by microdie transfer





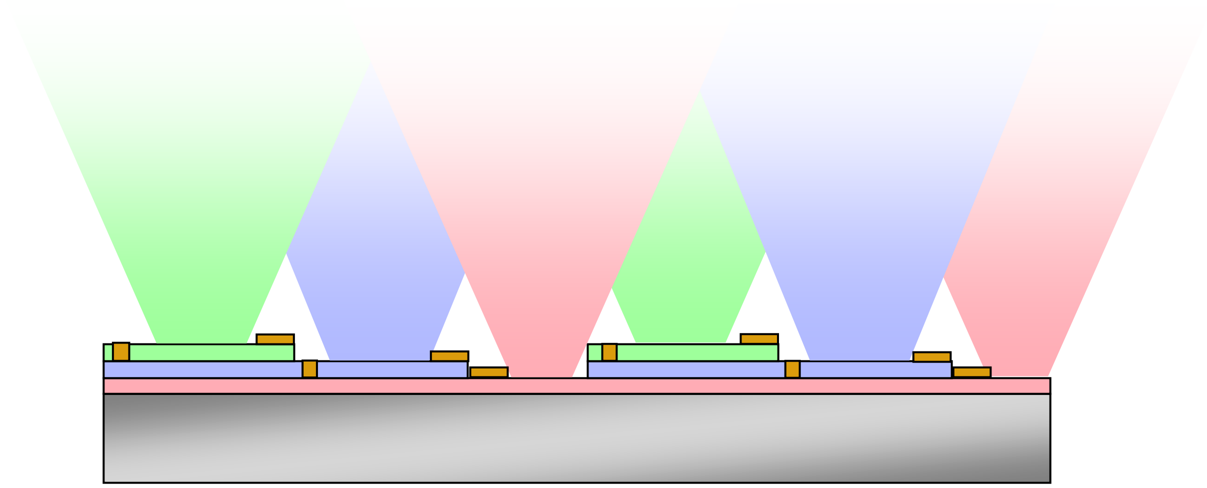
Dual wavelength Fluorescence Detection Microsystem with blue and green microdie LEDs transferred to Si by laser lift-off

Z. Luo, J.A. Chediak, J. Seo, N. Cheung, L.P. Lee and T.D. Sands, presented at the 2003 Electronic Materials Conference, Salt Lake City, June 25th, 2003

- *Potentially lower cost than multichip approach, but may be too complex and expensive for general illumination*

SSL approaches: *heteroepitaxy*

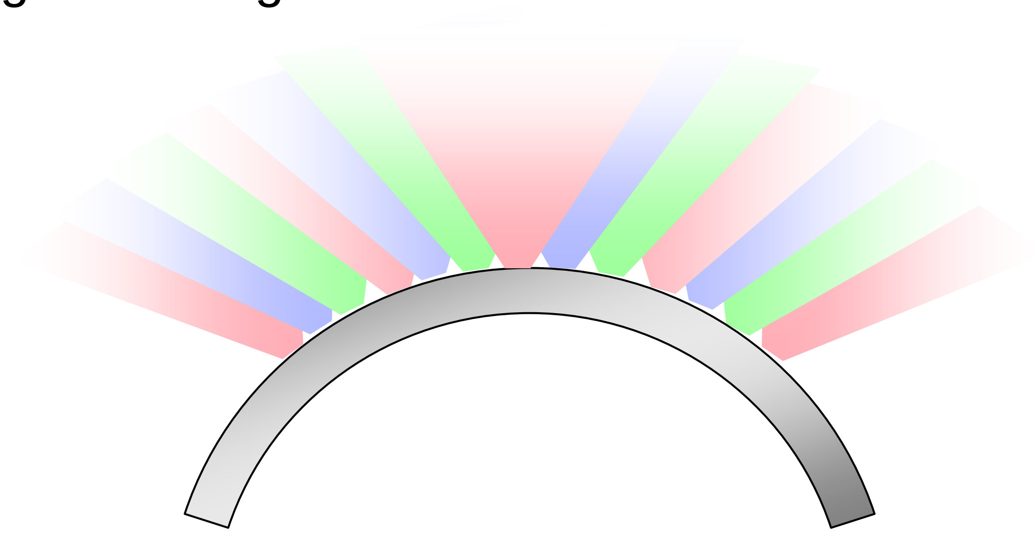
- Selective-area heteroepitaxy of (Al,Ga,In)N on (Al,Ga,In)(As,P) or vice versa



- *Eliminates layer transfer and bonding*
- *Creates problems associated with…*
  - *Incompatible growth and processing conditions*
  - *Defects due to symmetry, lattice, and CTE mismatch*
  - *Nonplanar surface*
  - *Multilevel metallization*

SSL approaches: *OLEDs*

- Organic Light-Emitting Diodes



- *Potentially low cost - fabricated by spin coating, thermal evaporation or ink jet printing*
- *Flexible - multiple colors on the same substrate*
- *Issues: efficiency (white), color uniformity, lamp lifetime, need for hermetic sealing*
- *Great for flexible displays - lifetime issue may preclude illumination applications*

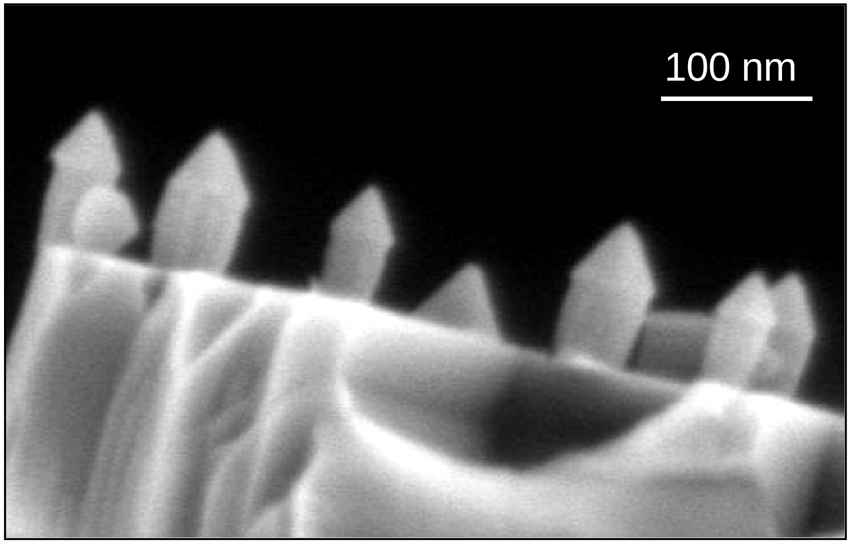
SSL approaches: *ideal?*

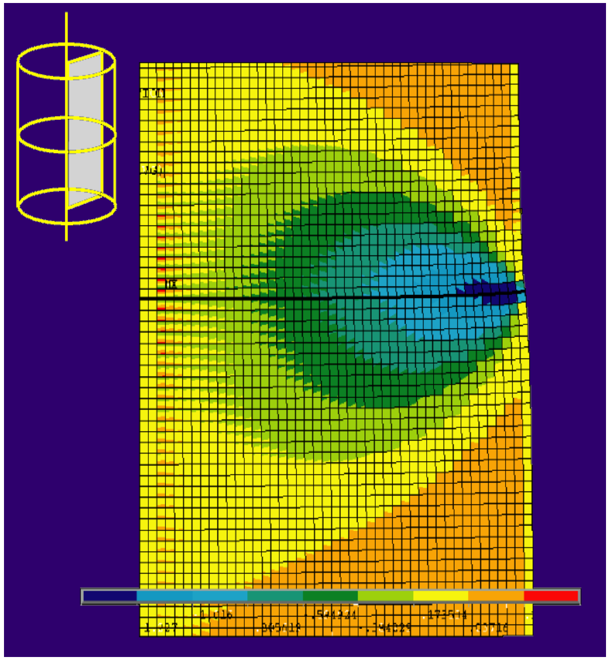
monolithic, phosphor-free white LED from one materials system

…(In,Ga)N??

Opportunities - *Nano*

- Nanoheteroepitaxy for strain-engineered phosphor-free white LEDs based on (In,Ga)N
- Photonic crystals and nanoplasmonics for enhanced coupling of light out of the semiconductor





Recommended Reading

- "Physics of Semiconductor Devices," Sze (Wiley, NY, 1981)
- "Introduction to Solid State Lighting," Zukauskas, Shur and Gaska (Wiley, NY, 2002)
- http://www.netl.doe.gov/ssl/

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Questions & Answers