

White Light Emitting Diodes

Erick J. Michel

emichel@kentlaw.edu

Energy Law

Spring 2009

Professor Bosselman

Outline

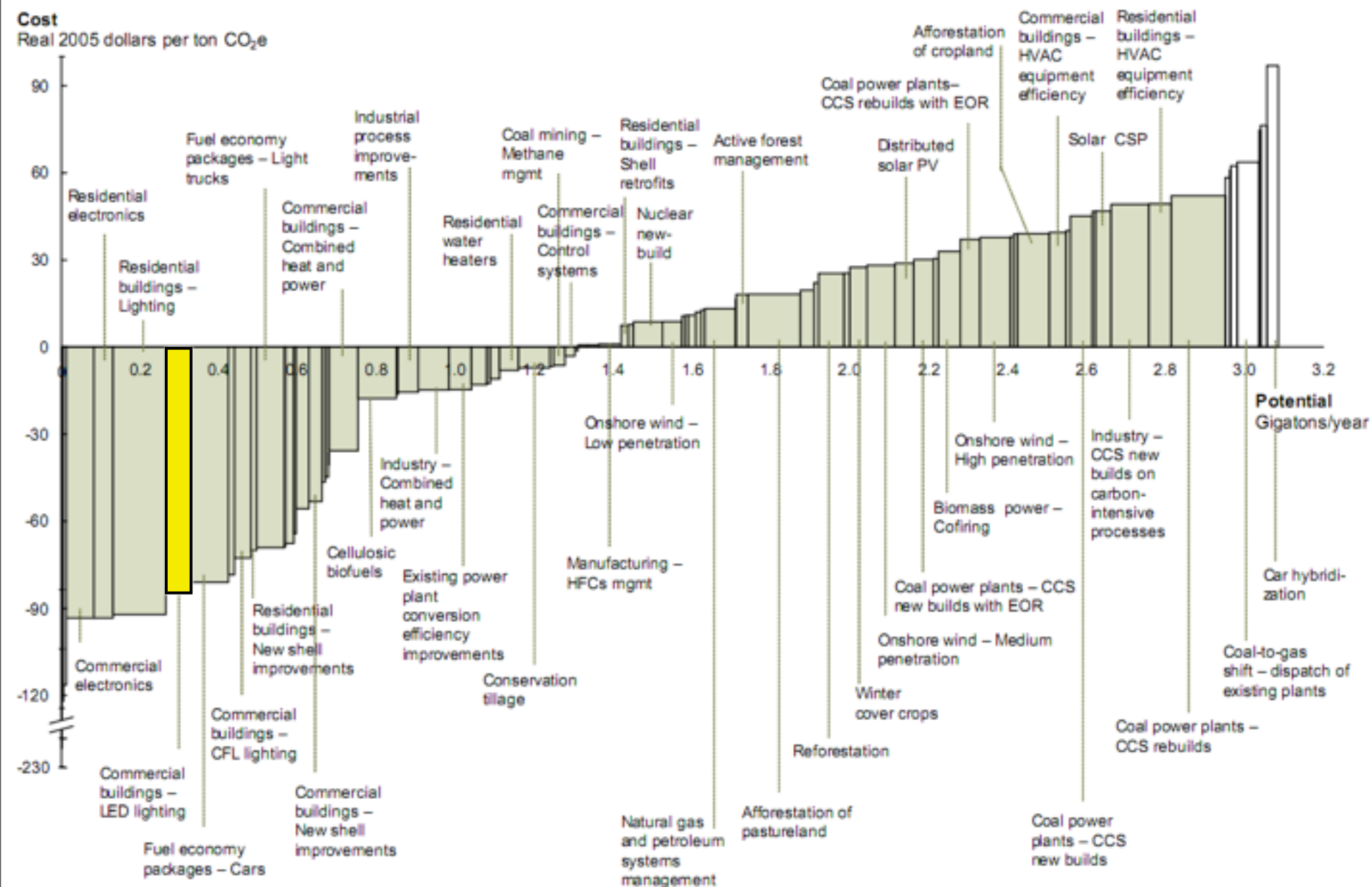
- Lighting Energy Use
- Types of Lighting
- Some Physics
- Generating White Light
- Issues/"Features"

Energy Used for Lighting

- $\frac{1}{3}$ of energy is used to generate electricity
- $\frac{1}{5}$ of electricity is used for lighting

U.S. MID-RANGE ABATEMENT CURVE – 2030

Abatement cost <\$50/ton



Source: McKinsey analysis

Public Policy

- Energy Independence and Security Act goal is to phase out incandescent bulbs in the 40-100 W range
- Replaced by halogen, compact fluorescent, LED lights, or other.
- Recommendation of 45 Lumens/Watt for GP lamps
- Has support of the current administration

BUT some resistance:

- Lightbulb Freedom of Choice Act
- Issues with testing uniformity (CALiPER)

Lighting Options

Incandescent



40W
1000 hours

Fluorescent



10W
10,000 hours

LED



1.5W
50,000 hours

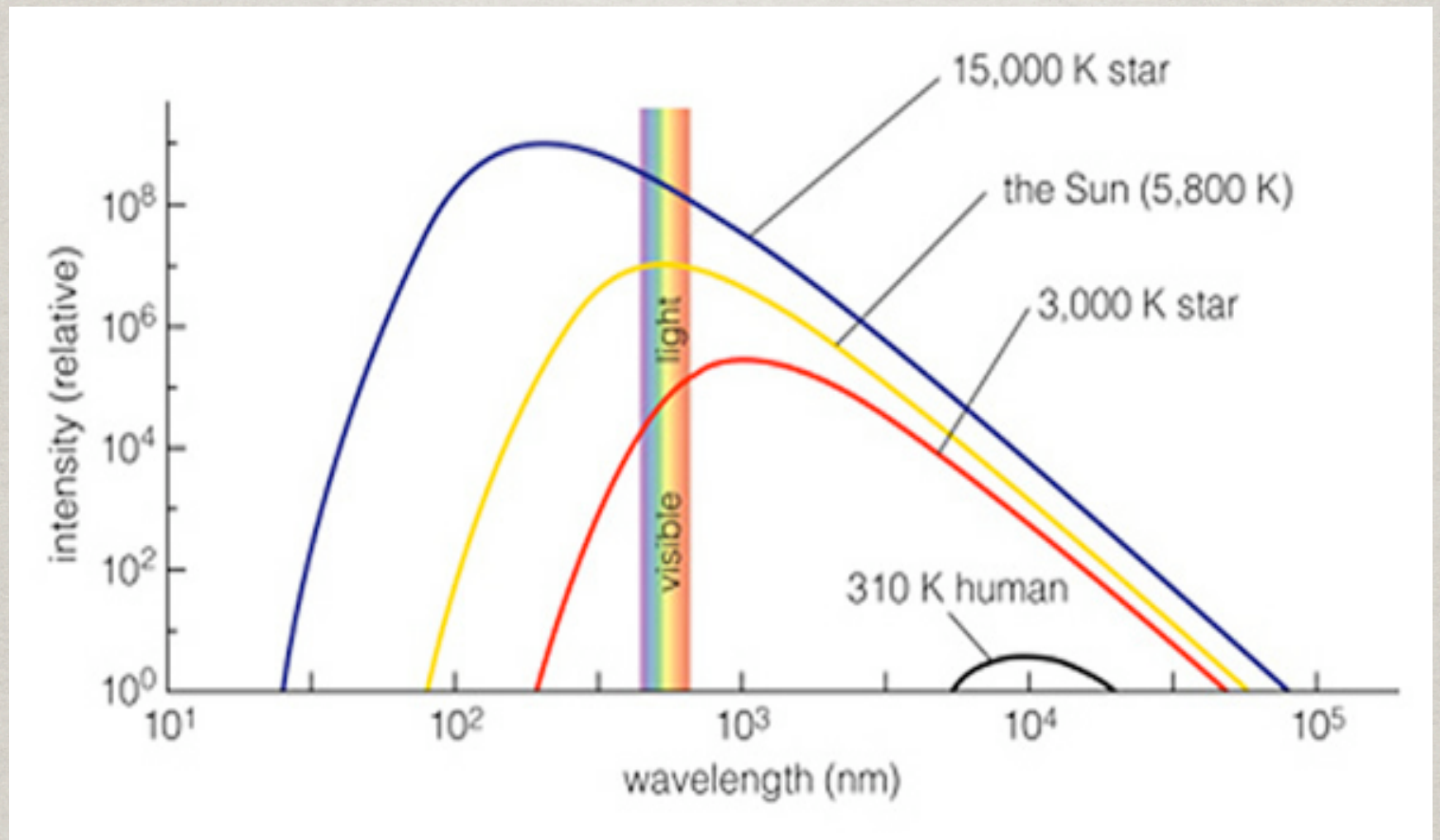
Why the difference?

Bulbs available at local hardware store.

Generation of Light

- Incandescence
- Fluorescence
- Luminescence

Incandescent Light



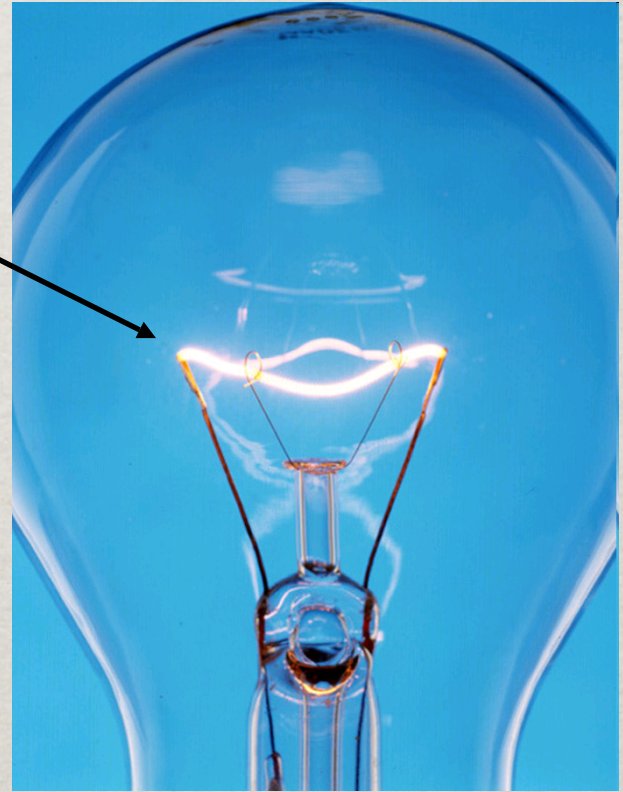
<http://www.thescienceforum.com/viewtopic.php?p=142514>

<http://www.ecse.rpi.edu/%7Eschubert/Light-Emitting-Diodes-dot-org/chap18/F18-02%20Planck%20black%20body.jpg>

Incandescent Light

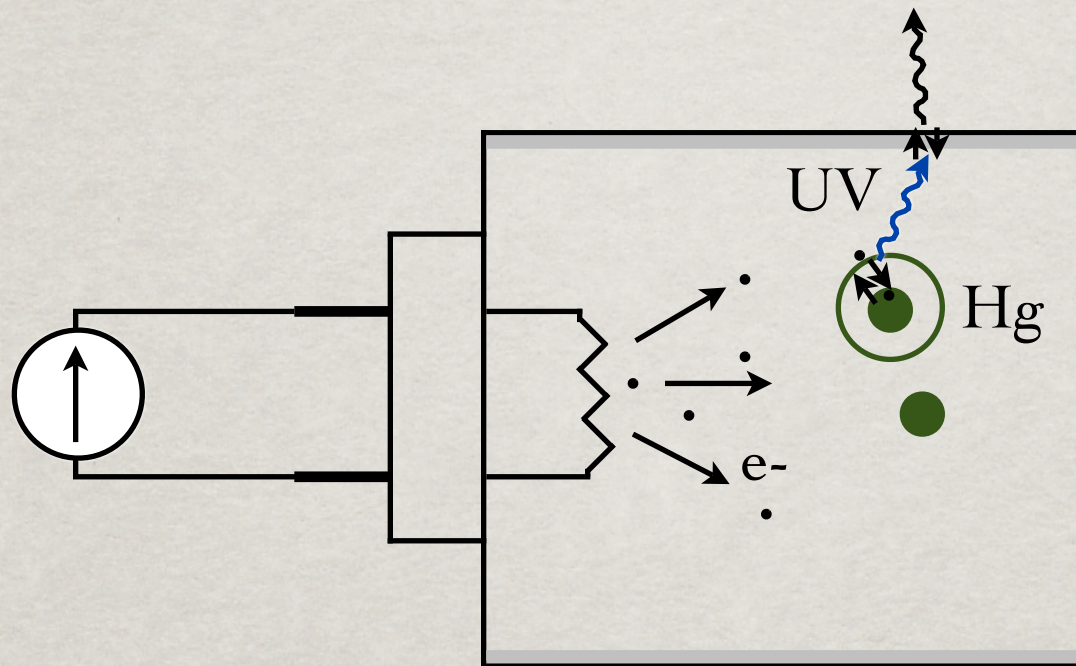
Tungsten Filament
 $T = 2700\text{-}3300$ Kelvin


About 95% of the energy
supplied to an incandescent bulb
is wasted as heat.



Chemistry. Prentice Hall, 1996: 443; "Electric Light." World Book Encyclopedia. World Book, 1998: 174-175; Bloomfield, Louis A. Incandescent Light Bulbs. How Things Work. University of Virginia; "Tungsten." A History of Technology. Oxford, 1958: 98-99; "Incandescent Lamp." Encarta. Microsoft, 1998; <http://www.newton.dep.anl.gov/askasci/eng99/eng99569.htm>

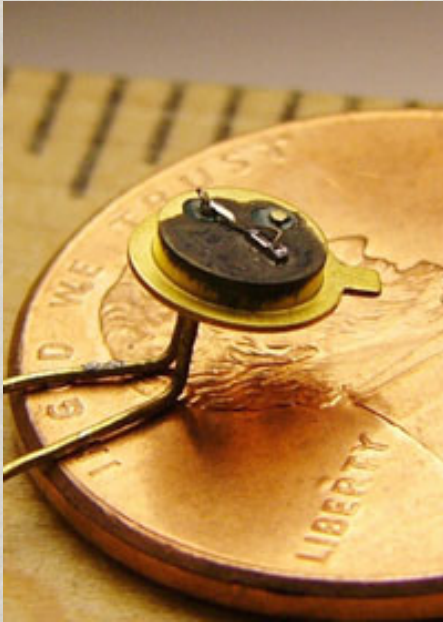
Fluorescent Light



- Inelastic Scattering and Fluorescence
- Hg 
- Switching reduces lifetime
- Inrush at startup

W filament coated with Ba, Sr, Ca oxides.
Ar, Xe, Kr, Ne with low P Hg vapor = 0.3 Atm.
Metallic and rare-earth phosphor salts

History of Light Emitting Diodes



1962 - First visible LED

Moved from red to green
through the 70's and 80's

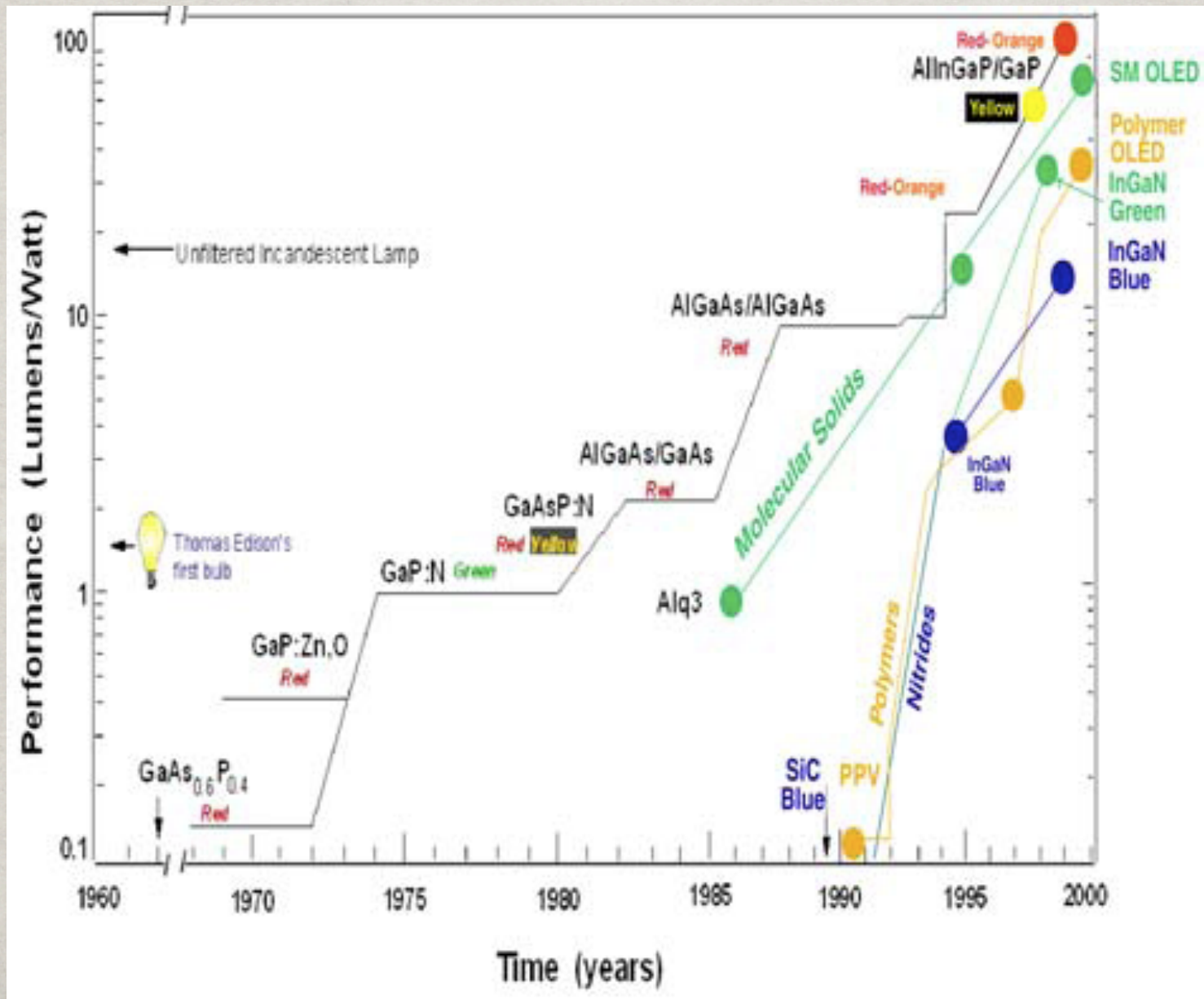


1995 - Blue LED

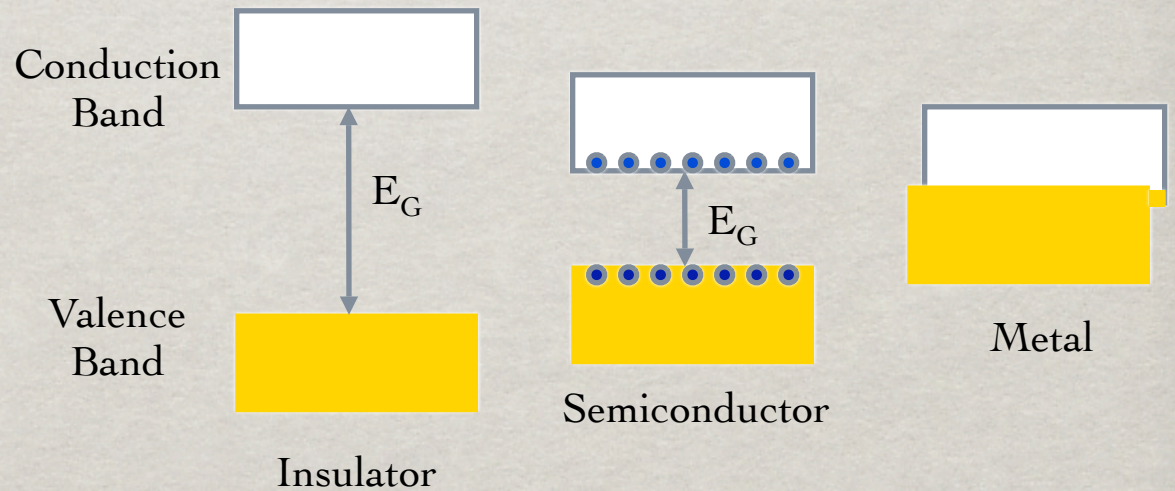
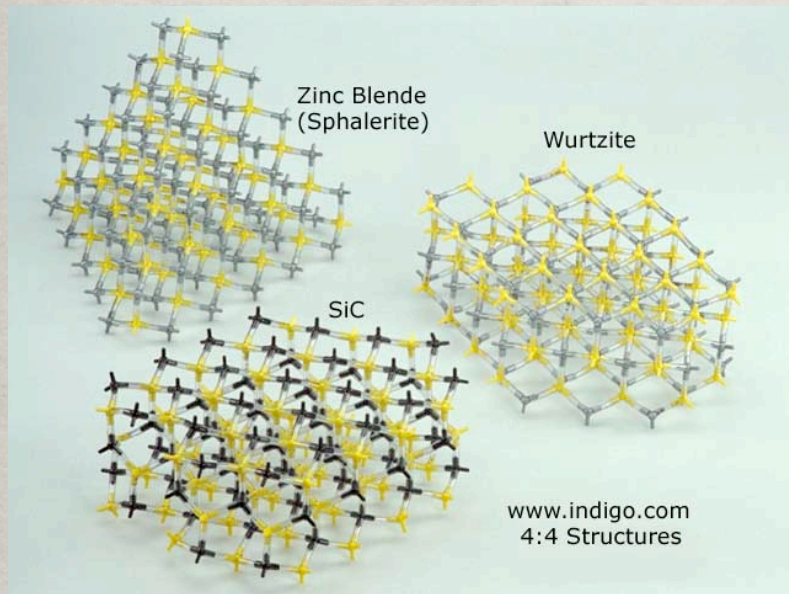


http://bmb.lcd.lu/science/230VAC_LED/index.html
Holonyak diode from www.spectrum.ieee.org/ may04/3986
Nick Holonyak at GE, later U of I
S. Nakamura of Nichia Corporation

History of LEDs



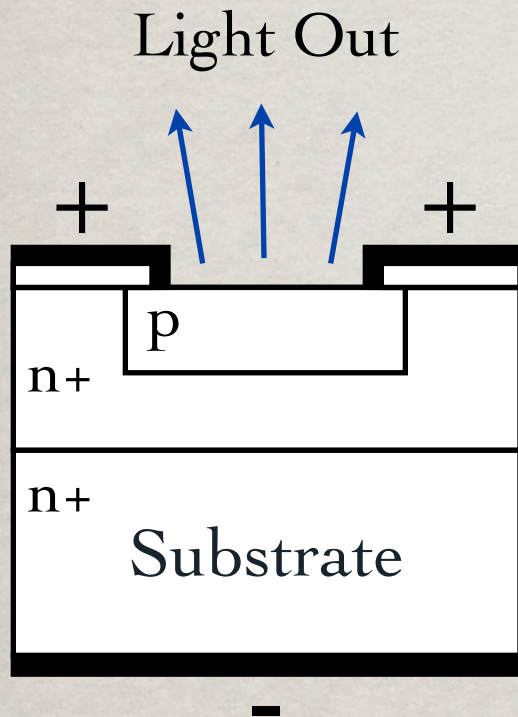
Some Physics of LEDs



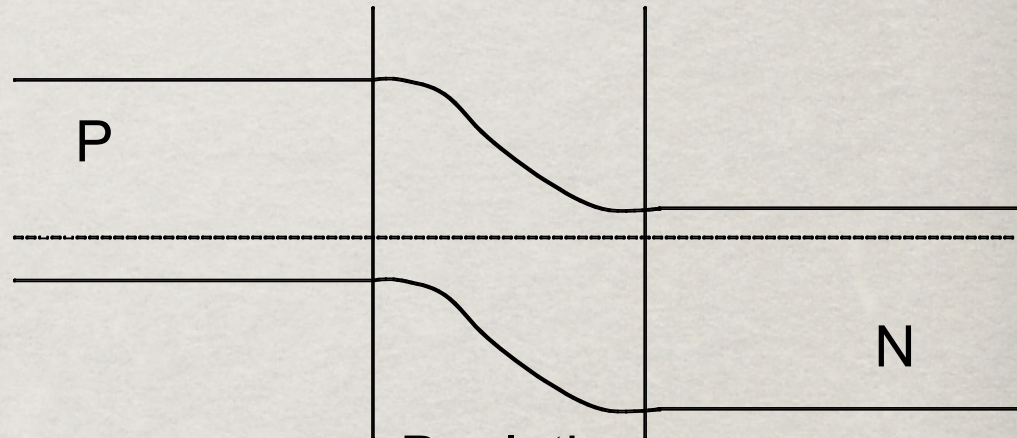
Periodic Table of the Elements

												III		V																	
												↓		↓																	
hydrogen 1 H 1.0079											boron 5 B 10.811		carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	helium 2 He 4.0026														
lithium 3 Li 6.941	beryllium 4 Be 9.0122											aluminum 13 Al 26.982		silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	neon 10 Ne 20.180													
sodium 11 Na 22.990	magnesium 12 Mg 24.305											gallium 31 Ga 69.723		germanium 32 Ge 72.61	arsenic 33 As 74.922	seelenium 34 Se 78.96	bromine 35 Br 79.904	argon 18 Ar 39.948													
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39					krypton 36 Kr 83.80															
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41					xenon 54 Xe 131.29															
cesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 ★	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59					radon 86 Rn [222]														
francium 87 Fr [223]	radium 88 Ra [226]	89-102 ★ ★	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununium 110 Uun [271]	ununium 111 Uuu [272]	ununium 112 Uub [277]																			
												ununquadium 114 Uuq [289]																			
* Lanthanide series																															
<table><tr><td>lanthanum 57 La 138.91</td><td>cerium 58 Ce 140.12</td><td>praseodymium 59 Pr 140.91</td><td>neodymium 60 Nd 144.24</td><td>promethium 61 Pm [145]</td><td>samarium 62 Sm 150.36</td><td>europium 63 Eu 151.96</td><td>gadolinium 64 Gd 157.25</td><td>terbium 65 Tb 158.93</td><td>dysprosium 66 Dy 162.50</td><td>holmium 67 Ho 164.93</td><td>erbium 68 Er 167.26</td><td>thulium 69 Tm 168.93</td><td>ytterbium 70 Yb 173.04</td></tr></table>																		lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
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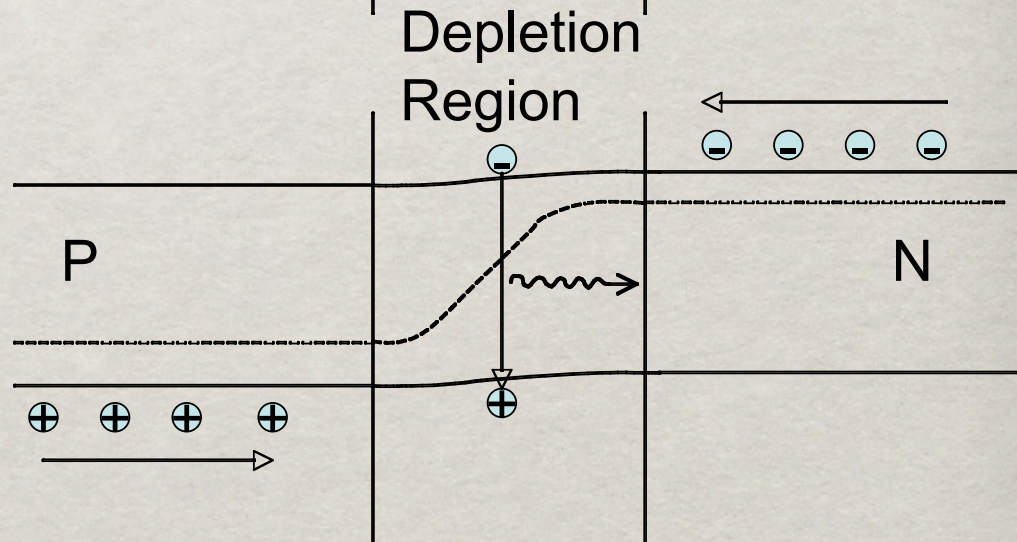
Some Physics of LEDs



Zero Bias



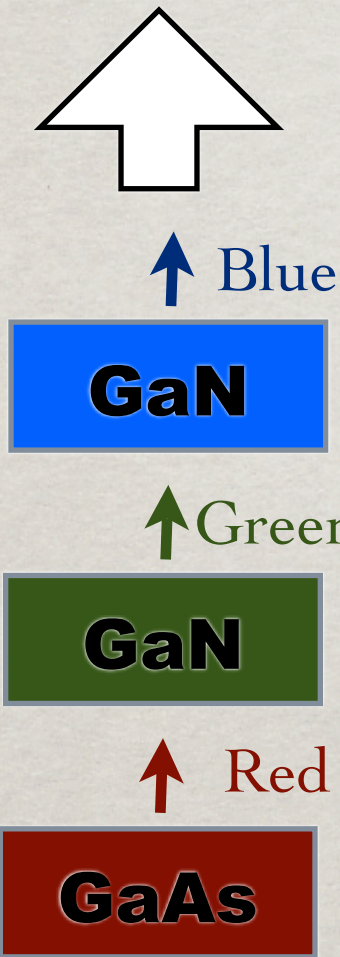
Forward Bias



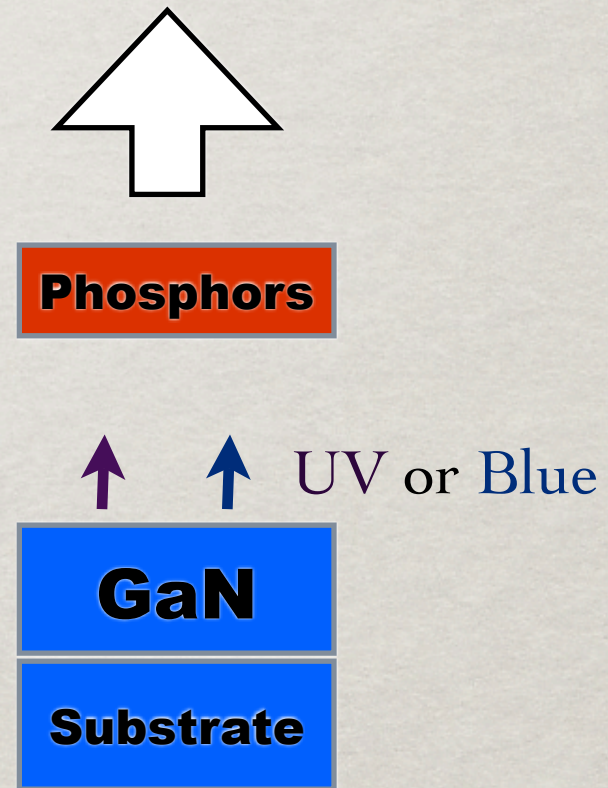
Diode created from p-type and n-type semiconductor layers

How to Make White Light

White Light



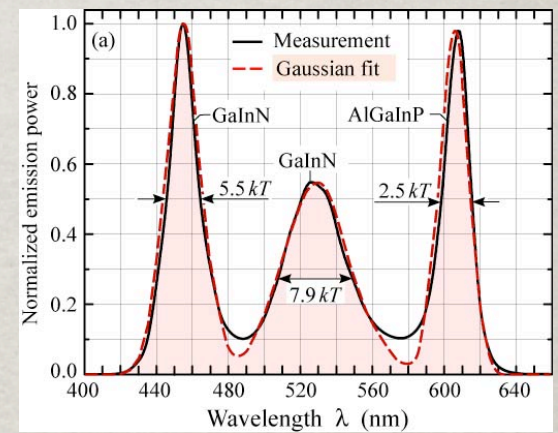
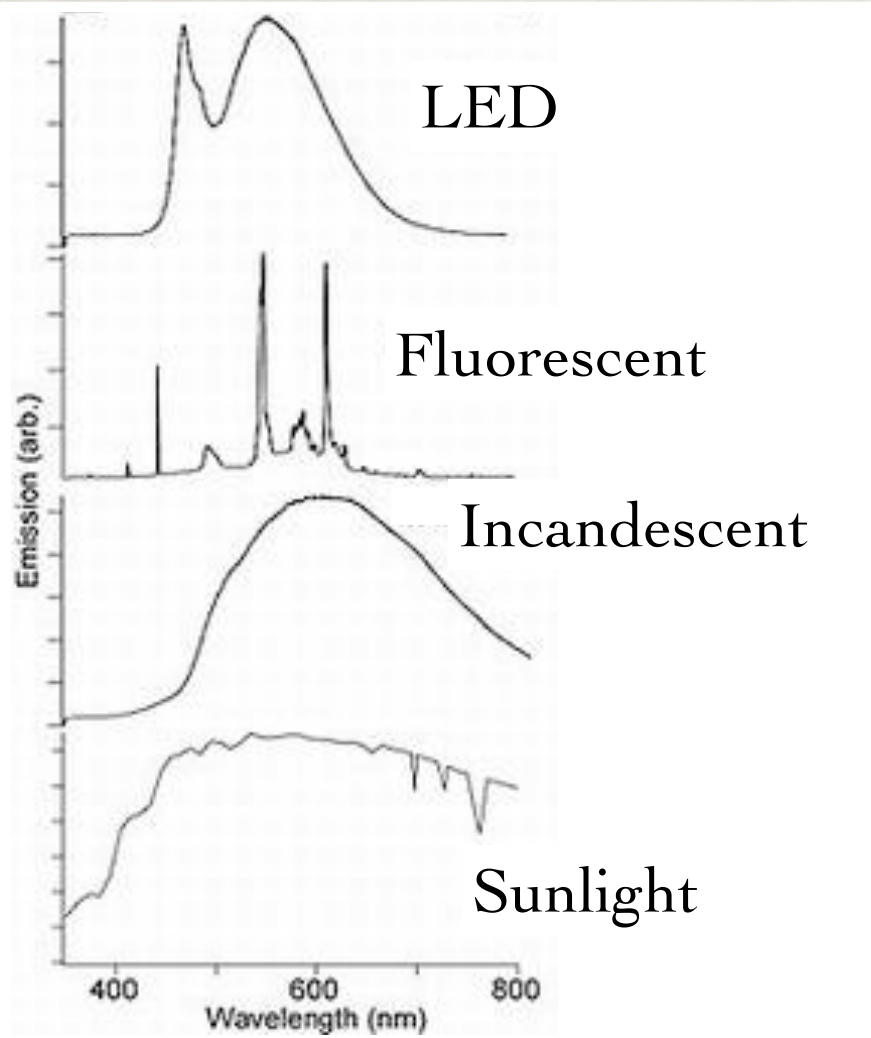
White Light



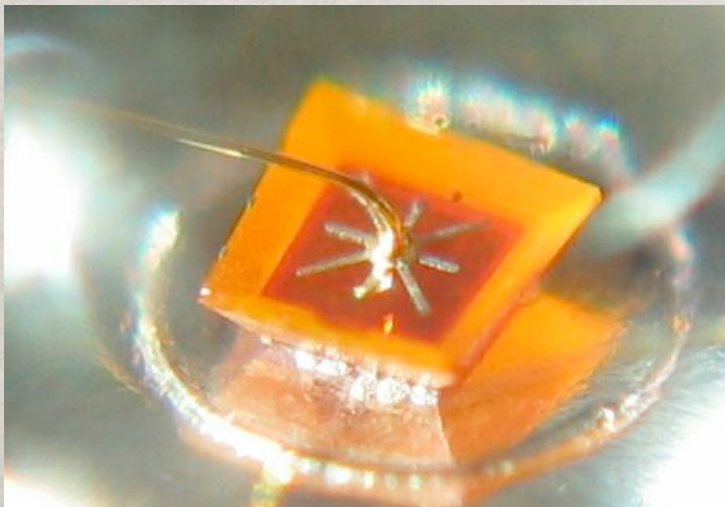
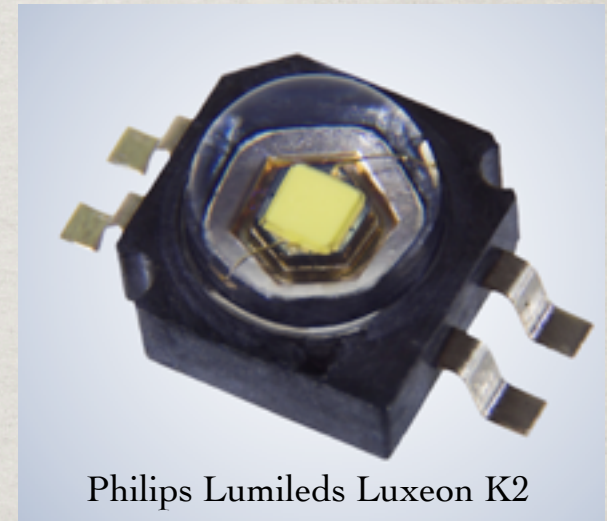
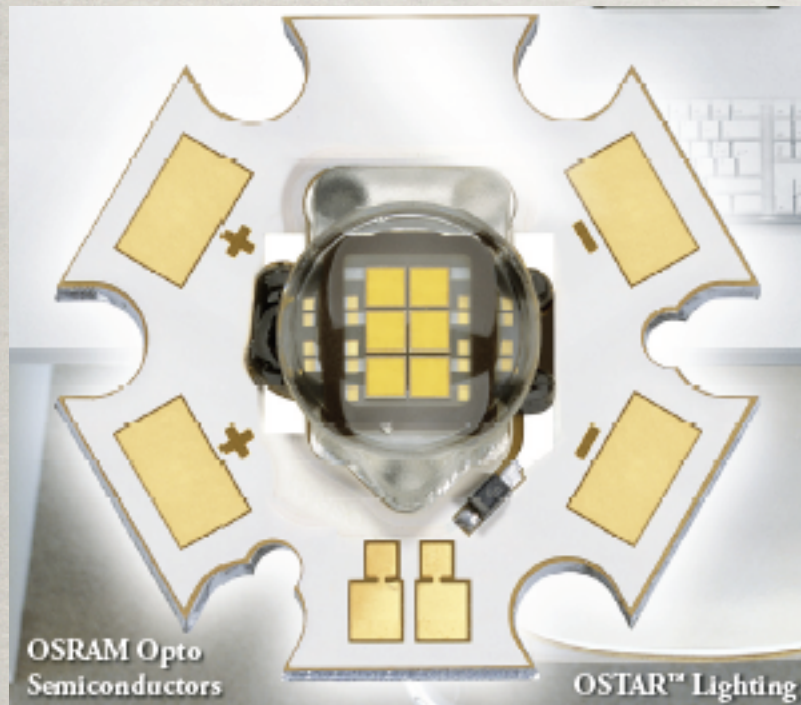
RGB : Pro - color flexibility; Con - temperature variation, control complexity, low CRI

Phosphor: Pro - Mature, high luminous flux, relatively high efficacy, lower cost;
Con High CCT, warmer CCT less available and more costly, color variability in beam.

Emission Spectra



Diode Packaging





66W Power Consumption

LED Efficacy ≥ 85 lumens/Watt

Illumination (E): (Height=6m) ≥ 27 Lux

"Futuramic thermal dissipation design, got patent."

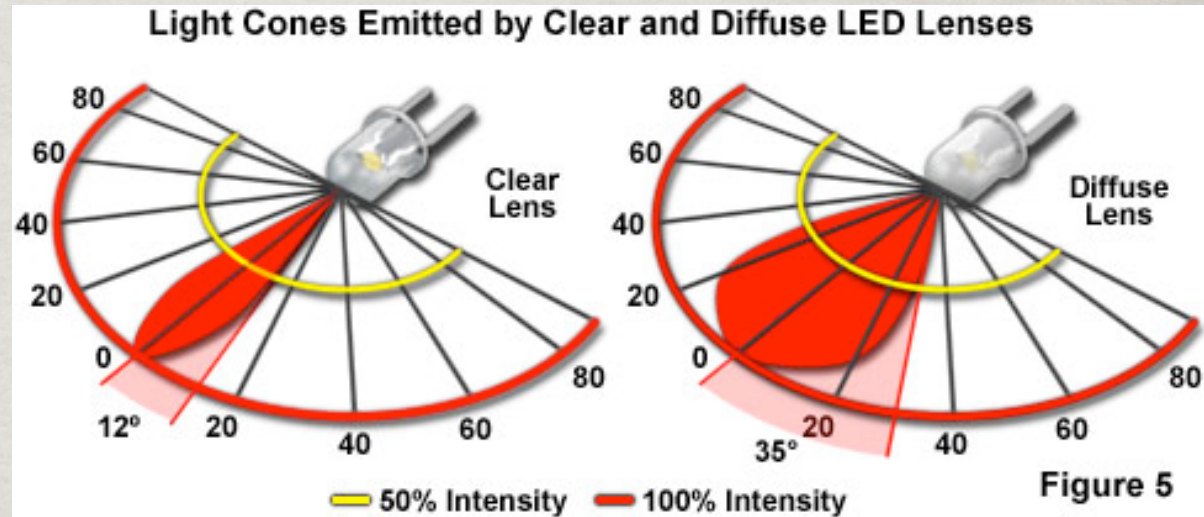
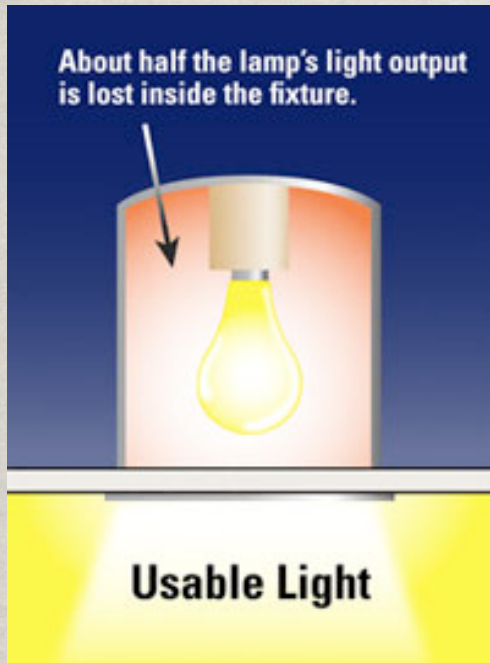
<http://www.made-in-china.com/showroom/cnzhled/product-detailqbSmQVFgZuhk/China-LED-Street-Light-ZH-L2W056-.html>

Issues/Features

- COST
- Lifetime
- Color
- Efficacy

Why the High Cost?

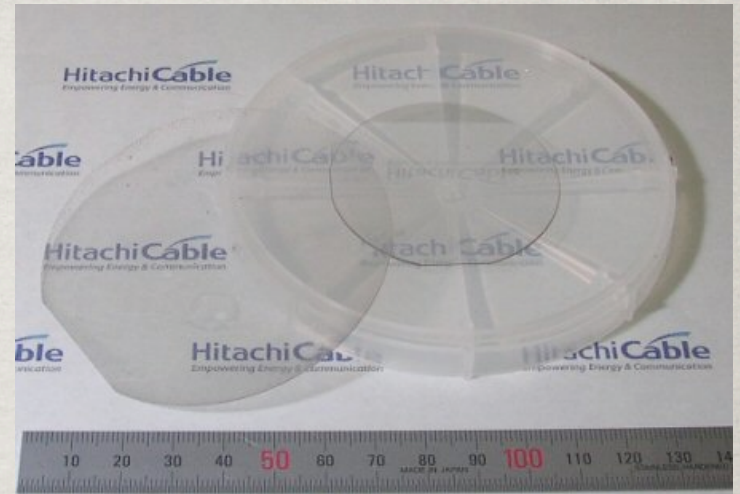
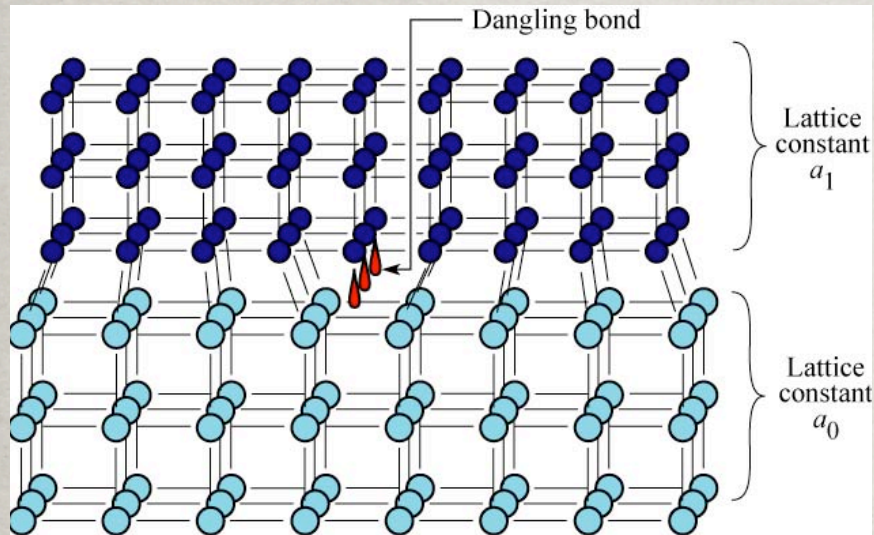
Diode Beam Shape - Packaging



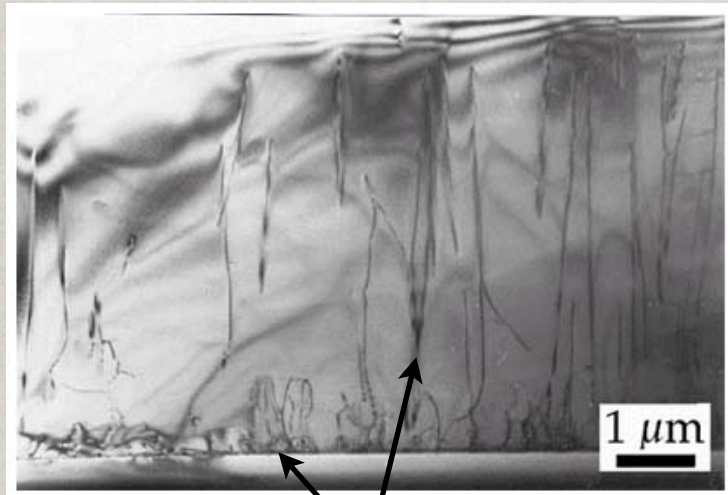
Growth of Semiconductor Materials

- Expensive Processes and Equipment
- Nitrides are difficult to grow
- Substrate Issues

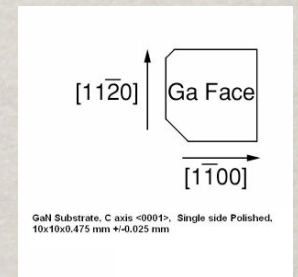
Substrate Issues



4" Al_2O_3 = \$400 2" SiC = \$1300



Dislocations



1 cm x 1 cm
GaN = \$1300

“Super Boule”

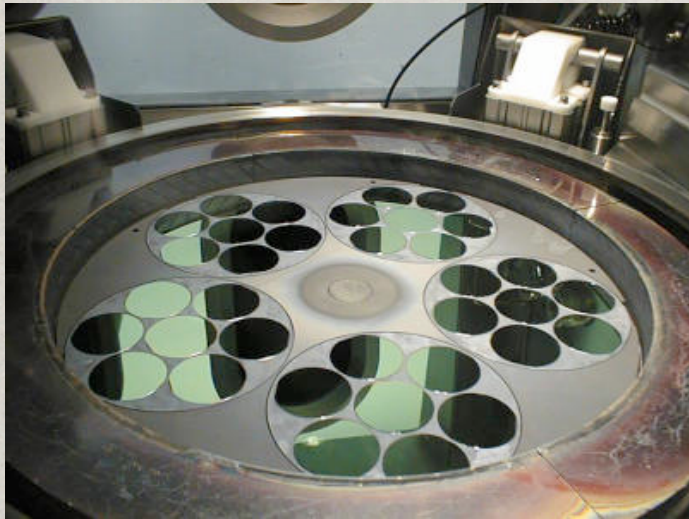
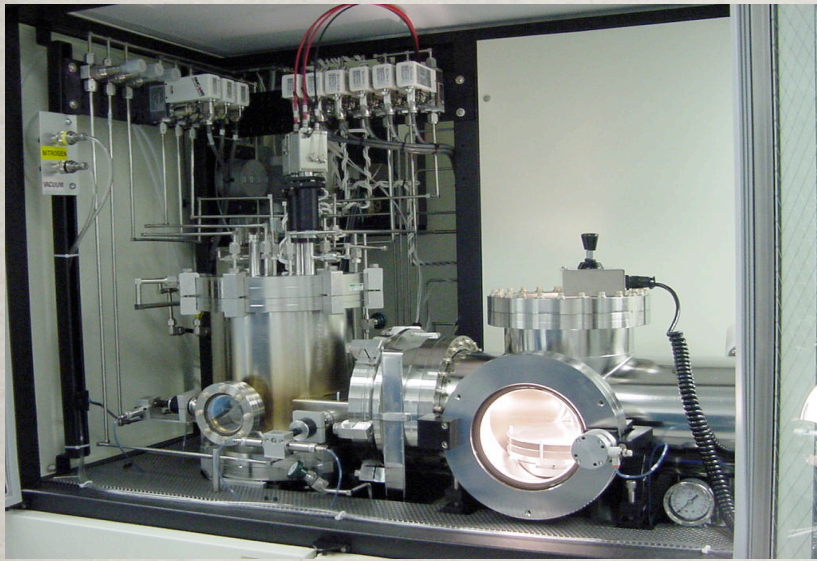
<http://www.ecse.rpi.edu/%7Eeschubert/Light-Emitting-Diodes-dot-org/chap07/F07-12%20Dislocations.jpg>

GaN on Sapphire - 2" = \$500-700 per wafer

Rubicon Sapphire super boule at <http://www.ledsmagazine.com/news/6/4/14>

Costs from www.mtixtl.com

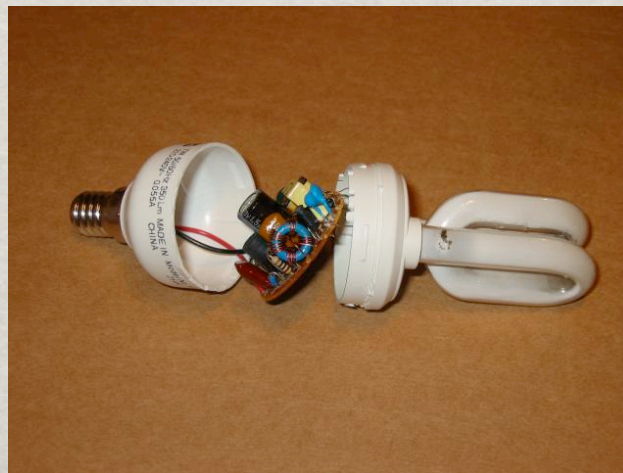
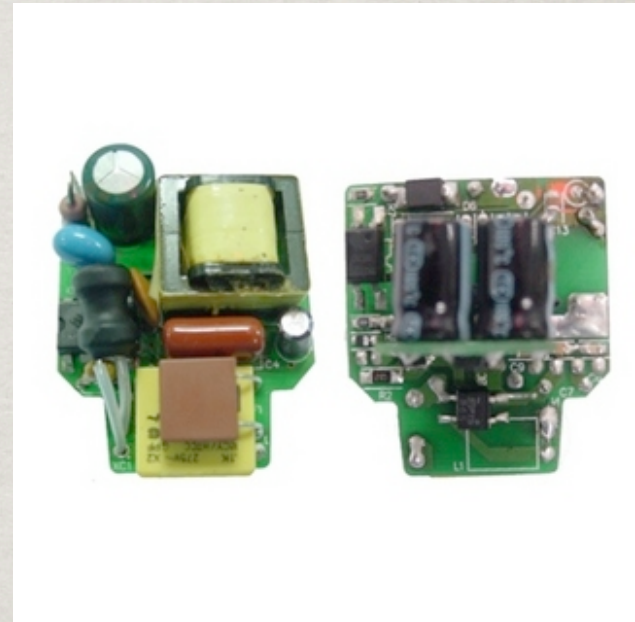
Growth of Semiconductor Materials



Metal-Organic Chemical Vapor Deposition

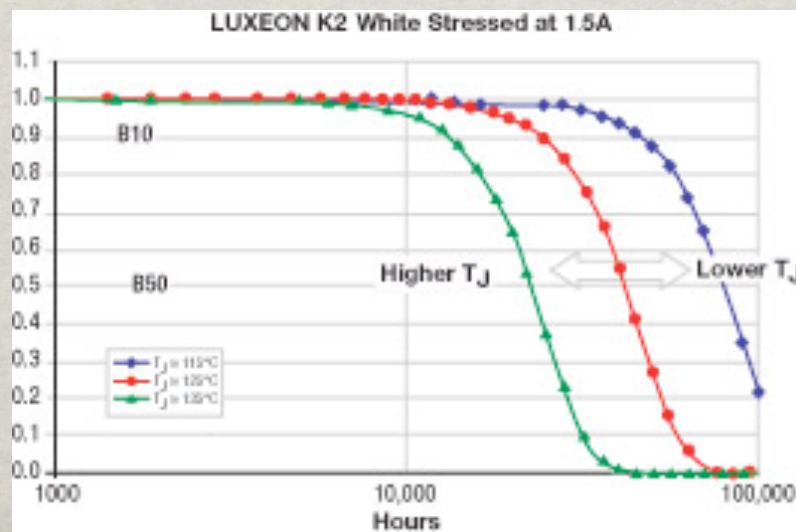
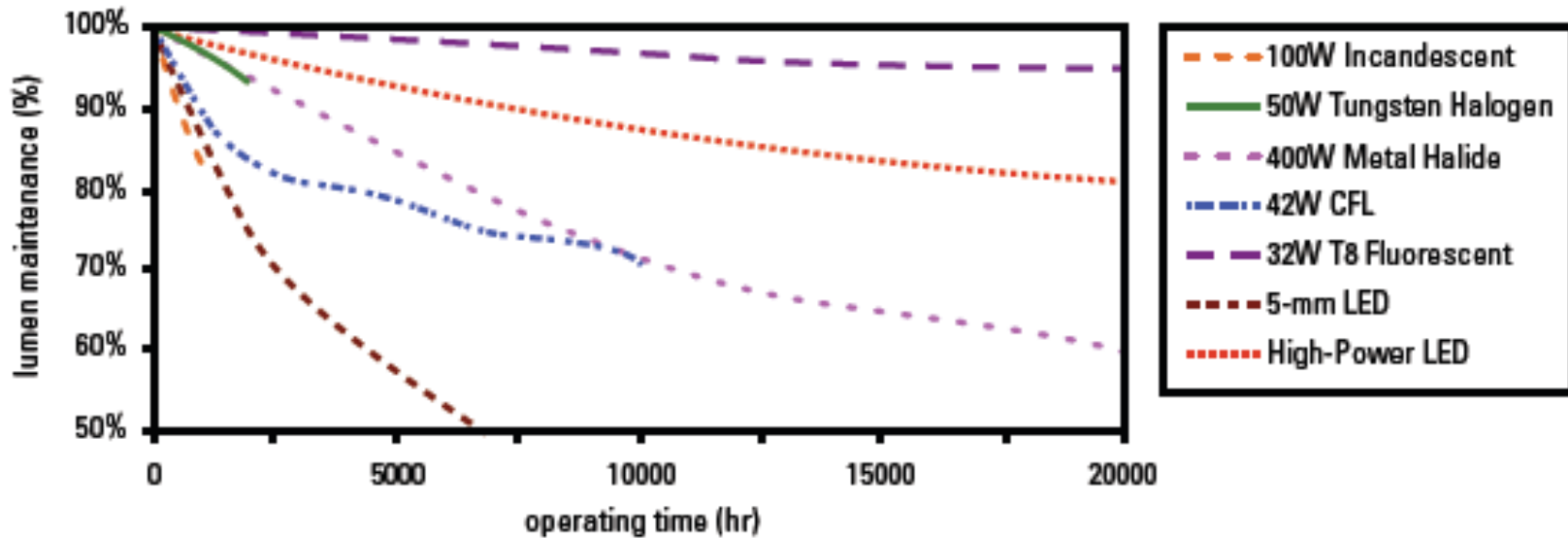
Agere Systems, Alentown, PA and www.aixtron.com

Driver Electronics



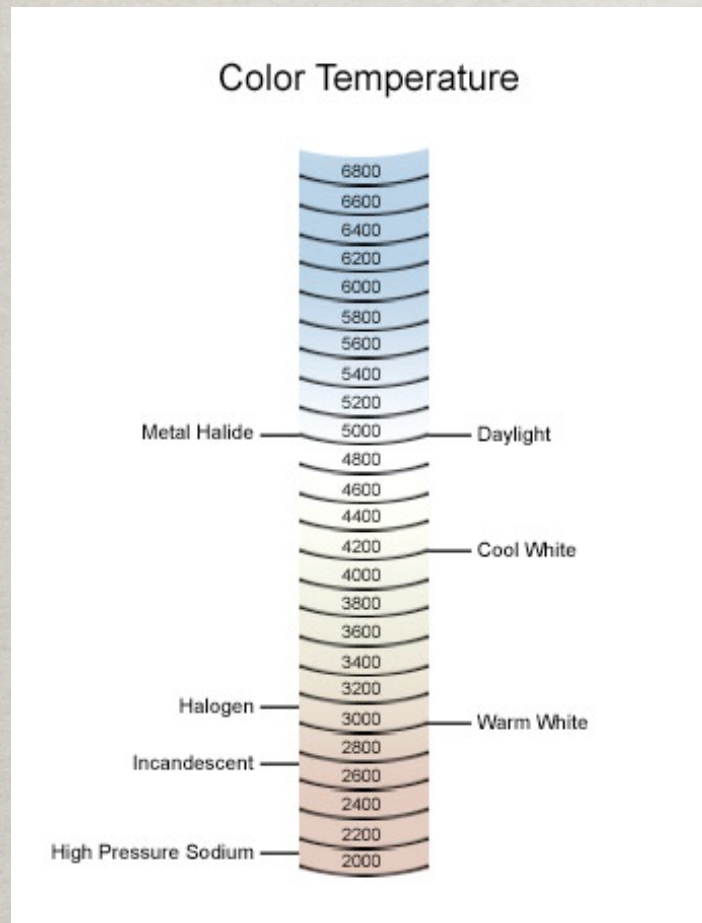
Diode Lifetime

Typical Lumen Maintenance Values for Various Light Sources



Bullough, J.D. 2003, Lighting Answers: LED Lighting Systems. Troy, NY, Lighting Research Center, RPI
 > 70% for general lighting.
 50,000 = 5.7 years, so devices are obsolete before they finish life testing.
 Estimating ~30,000 hours at $I = 350 \text{ mA}$ and $T_j < 90^\circ\text{C}$.
 Switching not relevant to LED lifetime.

Color Temperature



6400K Super Day Light



5000K Day Light



4100K Cool White

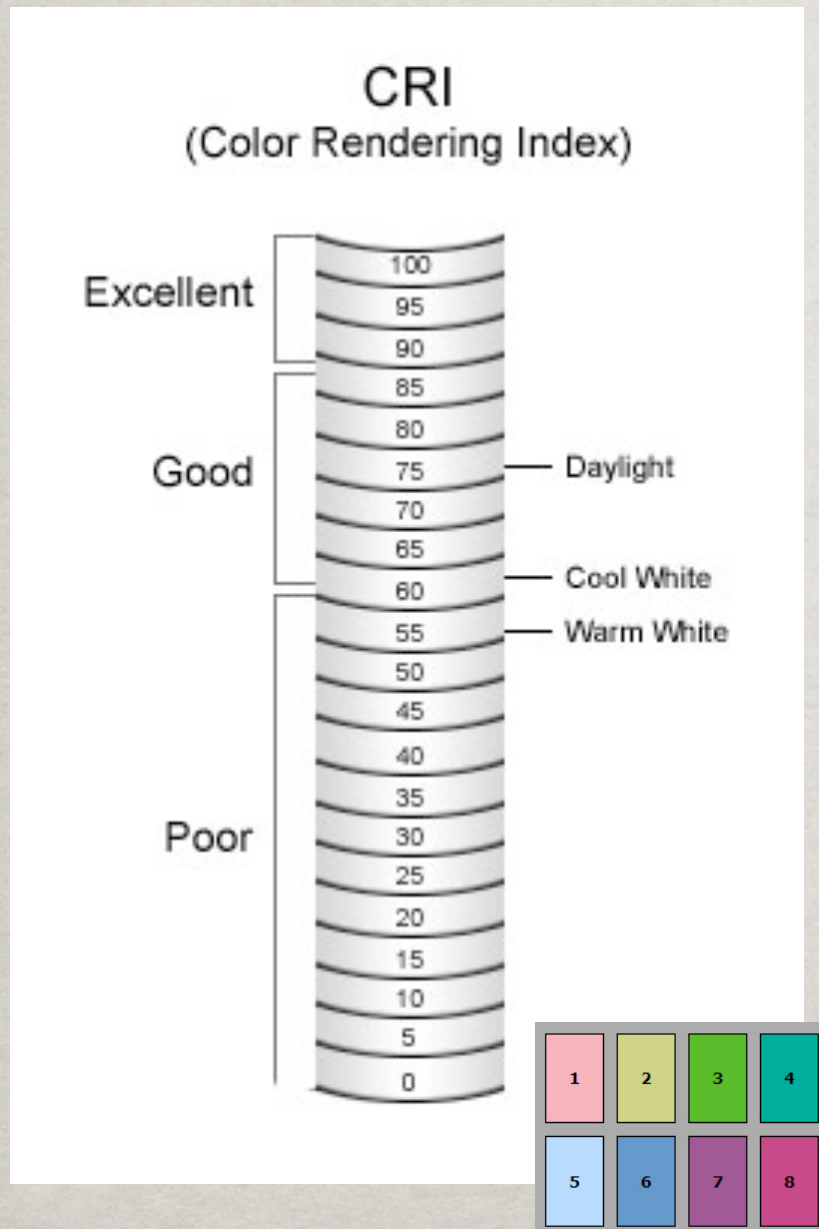


2700K Warm White

Correlated Color Temperature from US DOE:
<http://www1.eere.energy.gov/buildings/ssl/cct.html>

Color temperature is a description of the warmth or coolness of a light source. When a piece of metal is heated, the color of light it emits will change. This color begins as red in appearance and graduates to orange, yellow, white, and then blue-white to deeper colors of blue. The temperature of this metal is a physical measure in degrees Kelvin or absolute temperature. While lamps other than incandescent do not exactly mimic the output of this piece of metal, we utilize the correlated color temperature (or Kelvins) to describe the appearance of that light source as it relates to the appearance of the piece of metal (specifically a black body radiator). By convention, yellow-red colors (like the flames of a fire) are considered warm, and blue-green colors (like light from an overcast sky) are considered cool. Confusingly, higher Kelvin temperatures (3600–5500 K) are what we consider cool and lower color temperatures (2700–3000 K) are considered warm. Cool light is preferred for visual tasks because it produces higher contrast than warm light. Warm light is preferred for living spaces because it is more flattering to skin tones and clothing. A color temperature of 2700–3600 K is generally recommended for most indoor general and task lighting applications. Color Temperature is not an indicator of lamp heat.

Color



Lighting Research Center Study of lighting preferences



CRI varied from 20-70

Color Rendering Index from USDOE:

<http://www1.eere.energy.gov/buildings/ssl/cri.html>; and

<http://www.lightbulbsdirect.com/page/001/CTGY/CRI>

CRI, or Color Rendering Index, is a measurement of a light source's accuracy in rendering different colors when compared to a reference light source with the same correlated color temperature. It generally ranges from 0 for a source like a low-pressure sodium vapor lamp, which is monochromatic, to 100, for a source like an incandescent light bulb, which emits essentially blackbody radiation. The higher the CRI, the better the visual perception of colors. CRI is related to color temperature, in that the CRI measures for a pair of light sources can only be compared if they have the same color temperature ([see Color Temperature Chart](#)).

The highest attainable CRI is 100. Lamps with CRIs above 70 are typically used in office and living environments. A standard "cool white" fluorescent lamp will have a CRI near 62.

http://www.lrc.rpi.edu/programs/solidstate/cr_LEDReadingLights.asp

Efficacy (Light Output per Power Input)

Source	Luminous Efficacy (lm/W)
Incandescent	10-18
Halogen	15-20
Compact Fluorescent	35-60
Linear Fluorescent	50-100
Metal Halide	50-90
Cool White LED	47-64
Warm White LED	25-44

Recent LED results of 130 lm/W @ 5800K and 100 lm/W @ 2950K
Roadmaps predict up to 200 lm/W for LEDs

<http://www1.eere.energy.gov/buildings/ssl/efficacy.html>

Includes ballast or driver for fluorescents and LEDs (15%)

Organic LEDs



http://www.printedelectronicsworld.com/articles/europe_joins_ramp_d_forces_on_organic_led_technology_00000150.asp?sessionid=1
<http://www.ledsmagazine.com/news/6/4/13>

Some Holdouts?

