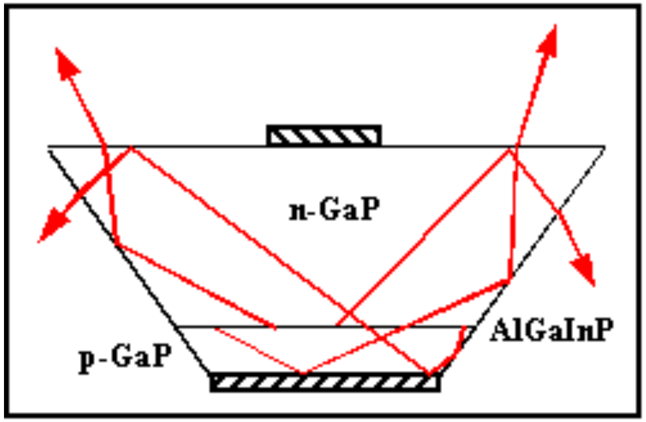
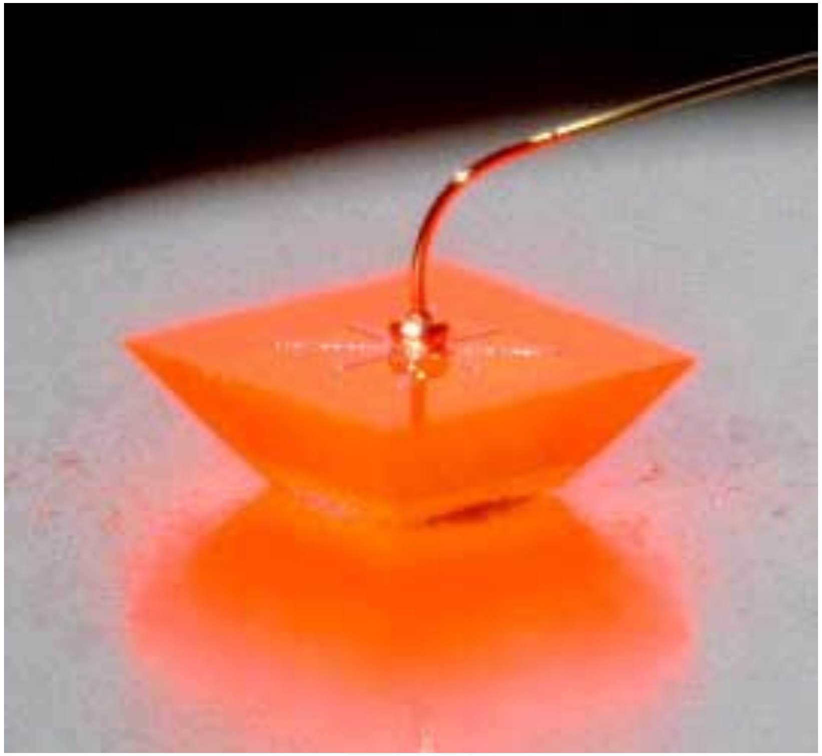
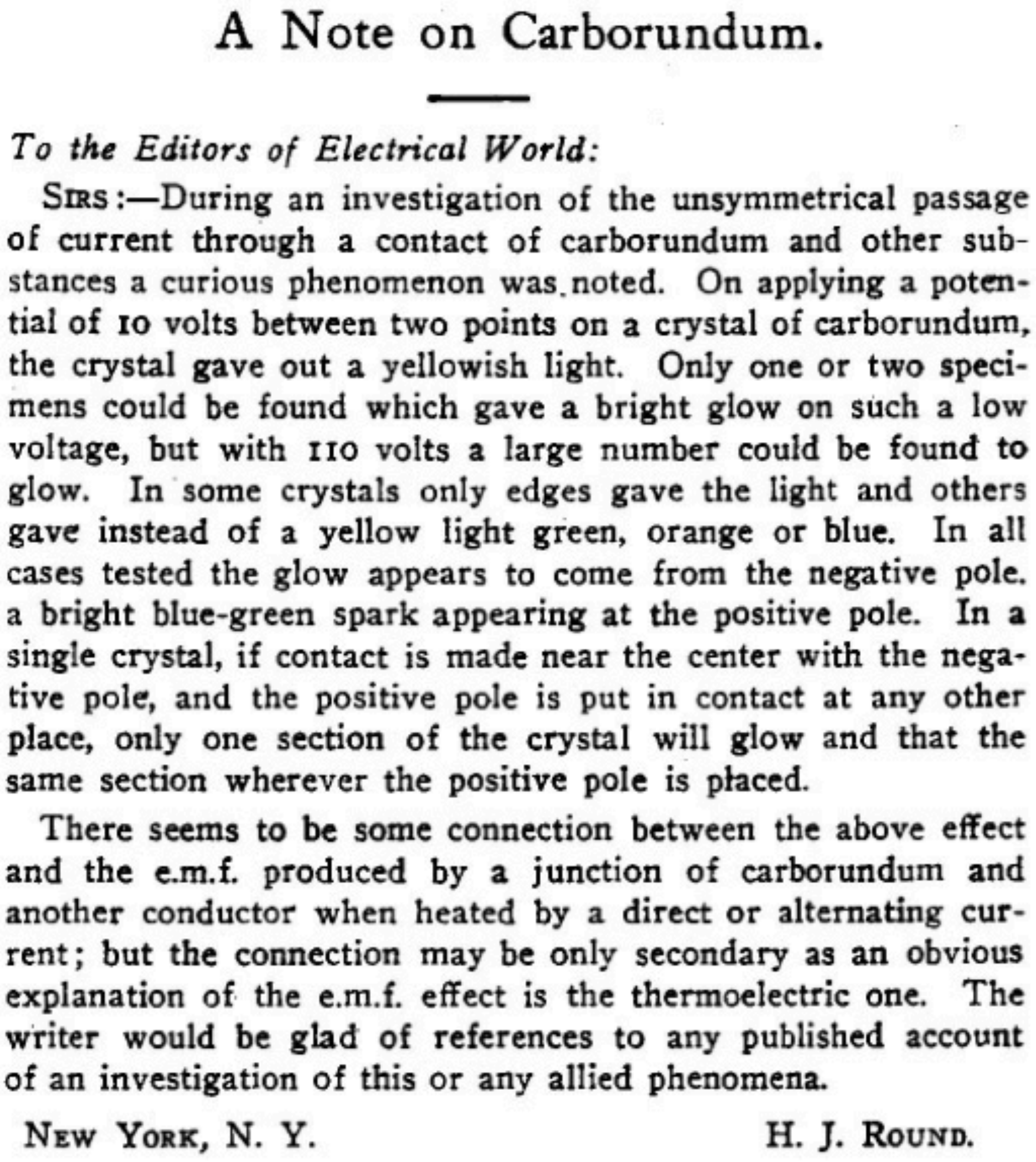
8.2 - Light Emitting Diodes / Solid State Lighting





A bit of history…



A Note on Carborundum.

To the Editors of Electrical World:

Sirs:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole. a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

New York, N. Y. H. J. Round.

Fig. 1.1. Publication reporting on a "curious phenomenon", namely the first observation of electroluminescence from a SiC (carborundum) light-emitting diode. The article indicates that the first LED was a Schottky diode rather than a pn-junction diode (after H. J. Round, *Electrical World* Vol. **49**, p. 309, 1907)

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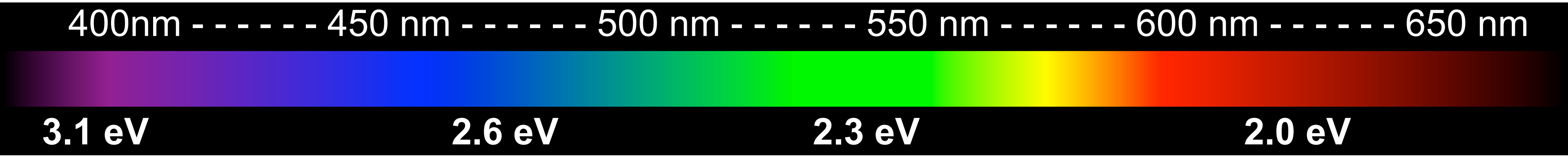
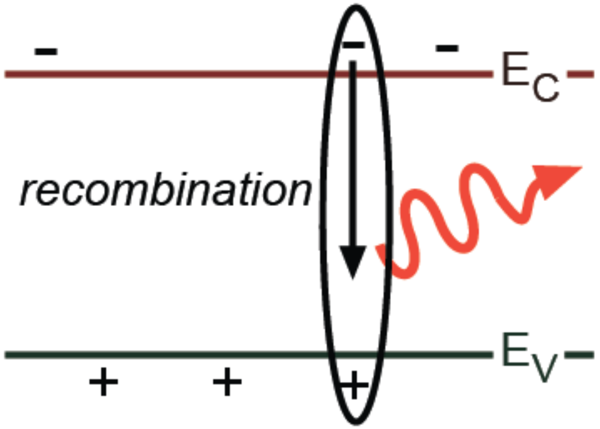
Light Emission by Recombination



- We already know how to calculate emission wavelength for a semiconductor!

$$E(eV) = hc/\lambda$$
$$\approx 1240/\lambda(nm)$$



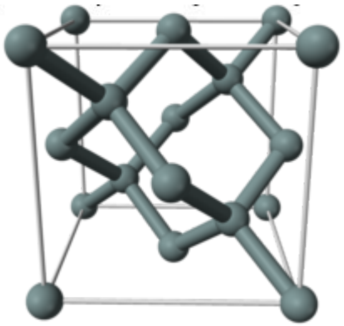
- Remember, all semiconductors can absorb photons larger than the bandgap (EH generation)…
- … but only direct-bandgap semiconductors emit light by EH recombination!
- Remember, there is always a doping dependence on lifetime, but the recombination factor (α_r) is different for radiative (GaN photon emitted) vs. non-radiative (like Silicon, just heat).

$$\tau_n = \tau_p = \frac{1}{\alpha_r(n_0 + p_0)}$$

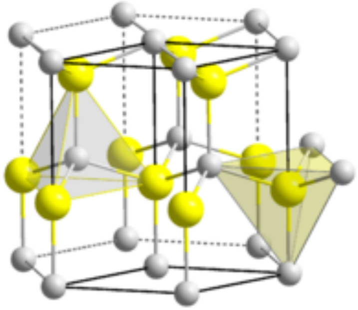
α_r depends on mechanism. Generally emitting photons or recombining at defects in the semiconductor (trap states in the band gap) is faster. Therefore α_r is an average value you look up, or measure, that changes with semiconductor quality and type!

Which Semicon used for LEDs?

- Si



- GaN



1	2….												3	4	5	6	7	8
hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												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	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												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	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	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	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	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 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	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr	radium 88 Ra	89-102 ∗ ∗	lawrencium 103 Lr	rutherfordium 104 Rf	dubnium 105 Db	seaborgium 106 Sg	bohrium 107 Bh	hassium 108 Hs	meitnerium 109 Mt	ununnilium 110 Uun	unununium 111 Uuu	ununbium 112 Uub		ununquadium 114 Uuq				

- IV (4) semicon., indirect, narrow (Ge) to wide bandgap (SiC), low cost/common.
- II-VI (2-6) semicon., many direct, (CdSe) to wide bandgap (ZnO), emerging for transistors!
- III-V (3-5) semicon., many direct, really narrow (InSb) to really wide bandgap (AlN), nitrides are super durable but hard to make.
- Nearly all LEDs are based on III-V materials, why not II-VI? Which is more stable, a highly ionic bond like NaCl, or a highly covalent bond like Diamond (C-C)?

Which Semicon used for LEDs?

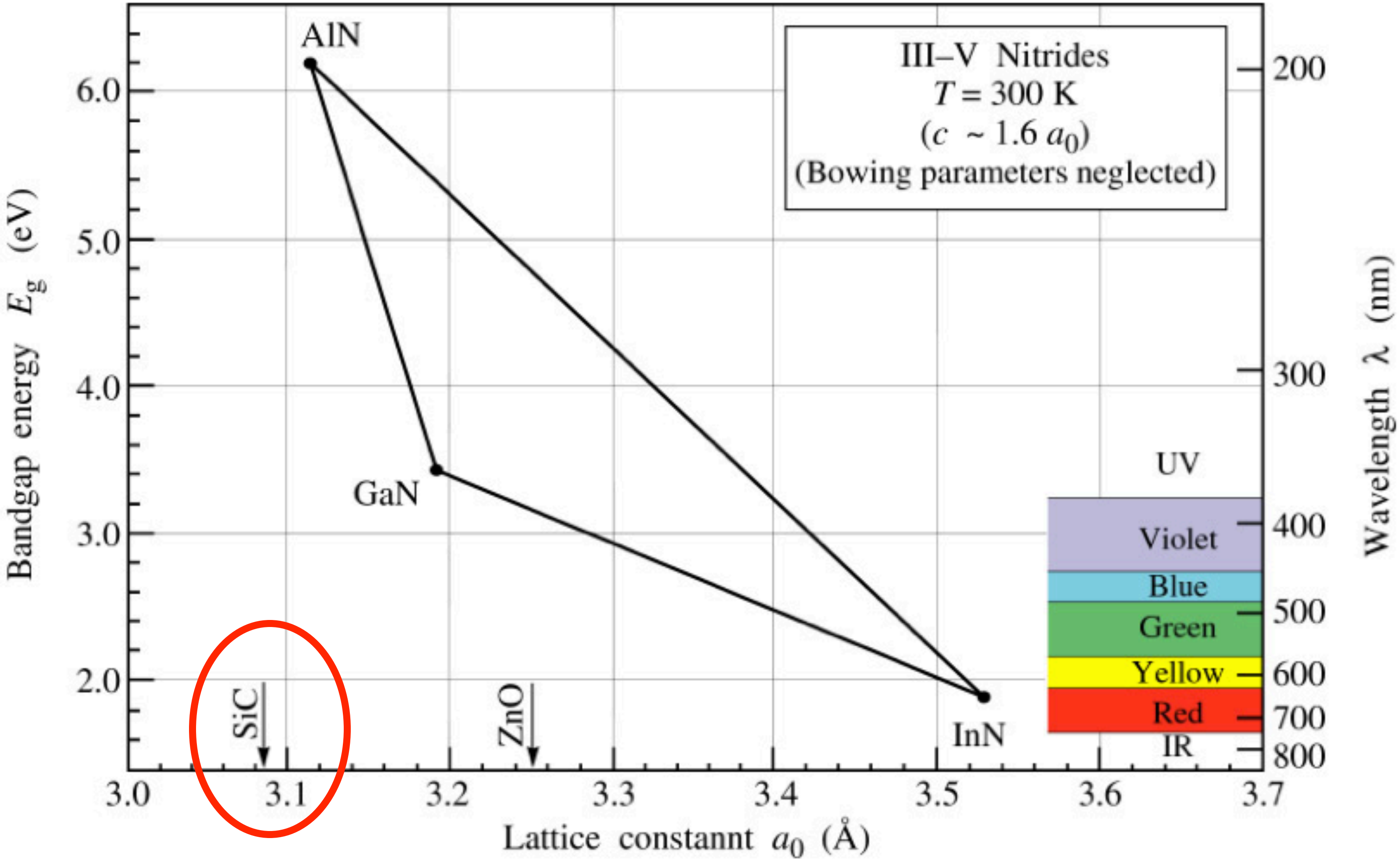


Fig. 8.12. Bandgap energy versus lattice constant of III-V nitride semiconductors at room temperature.

- There are no nitride (GaN etc.) substrates… SiC is widely used for GaN, but why is this an issue for blue/green LEDs? ☆

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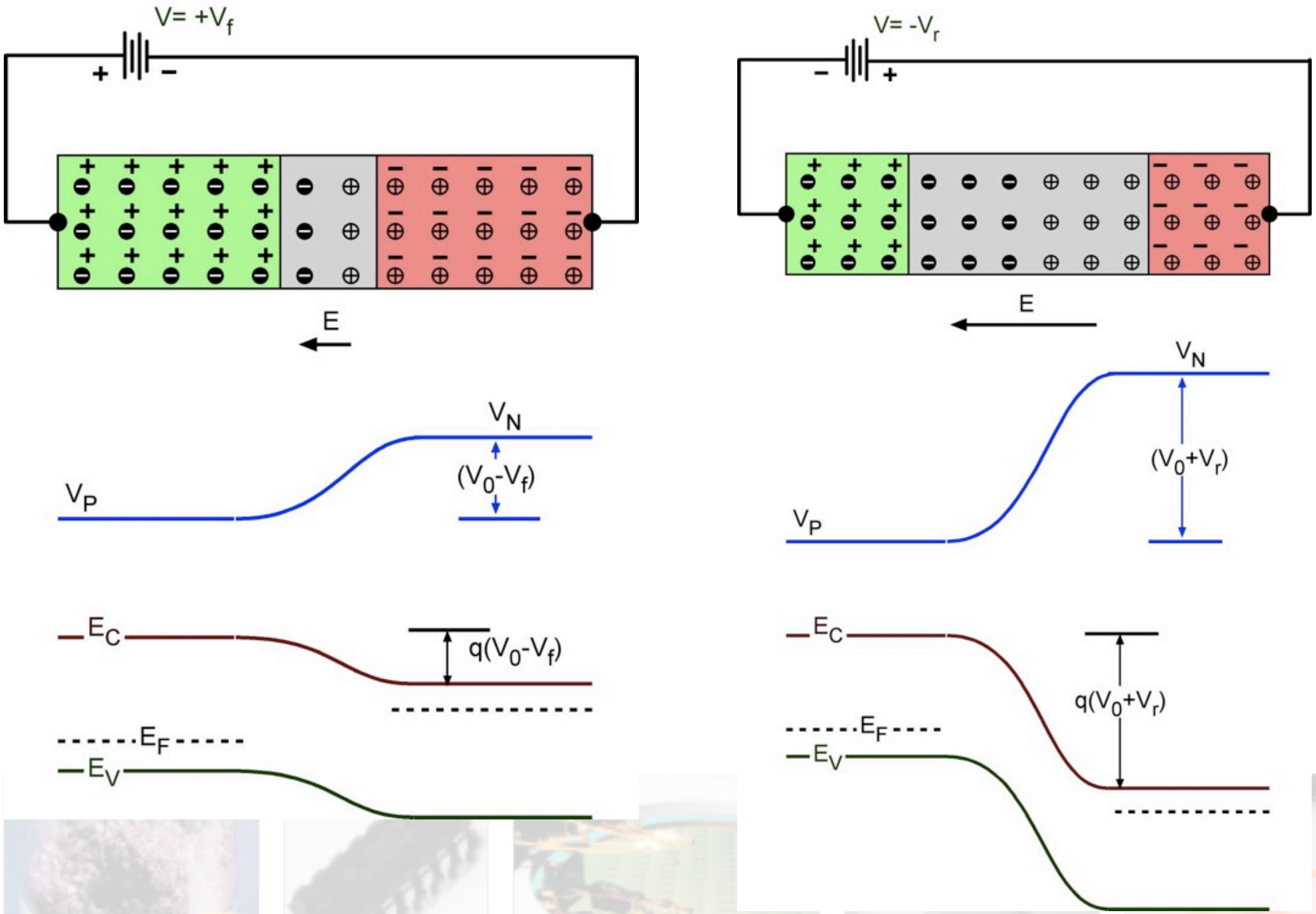
Light Emitting Diodes…

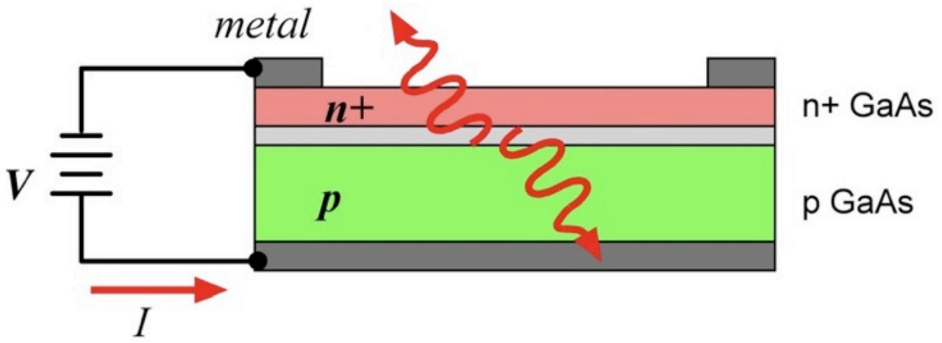
- How do we predict LED behavior? Do we need to re-derive?
- Will an LED emit light in reverse bias? (think practically…)
- Measure two diodes (one is an LED). At 20 mA, which is ‘hotter’ ?



Good LED Design…

- Why need thin n+ at the top? This fixed one problem…

- See any other problems at right with the design?

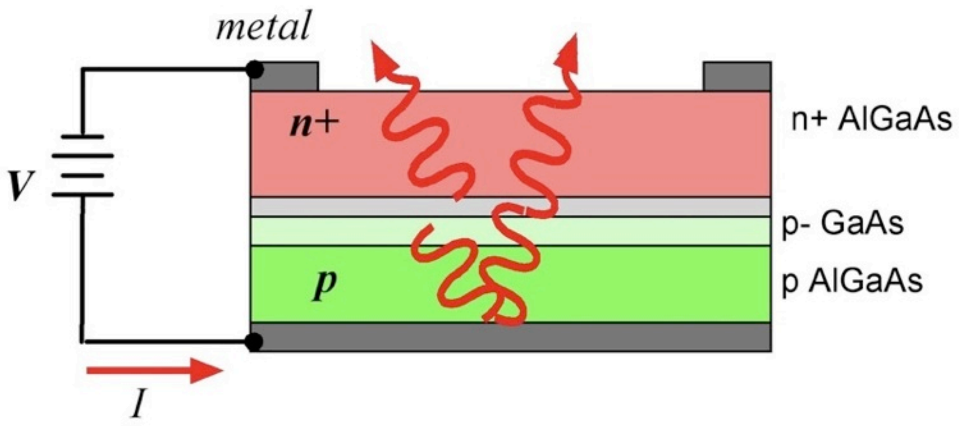


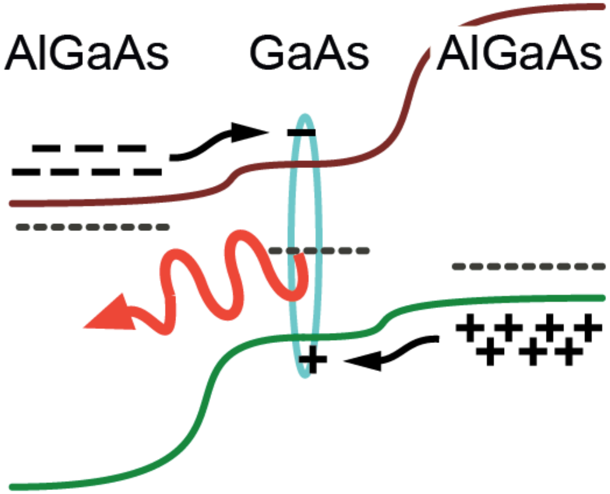
- Problems with this design…

(1) surface states at n+/air (dangling bonds) lead to non-radiative recombination
(2) The bottom p-layer is still thick (has to be as a *substrate*) so all light going toward p-region is absorbed (e-h generation)

How can we fix this?

Good LED Design…



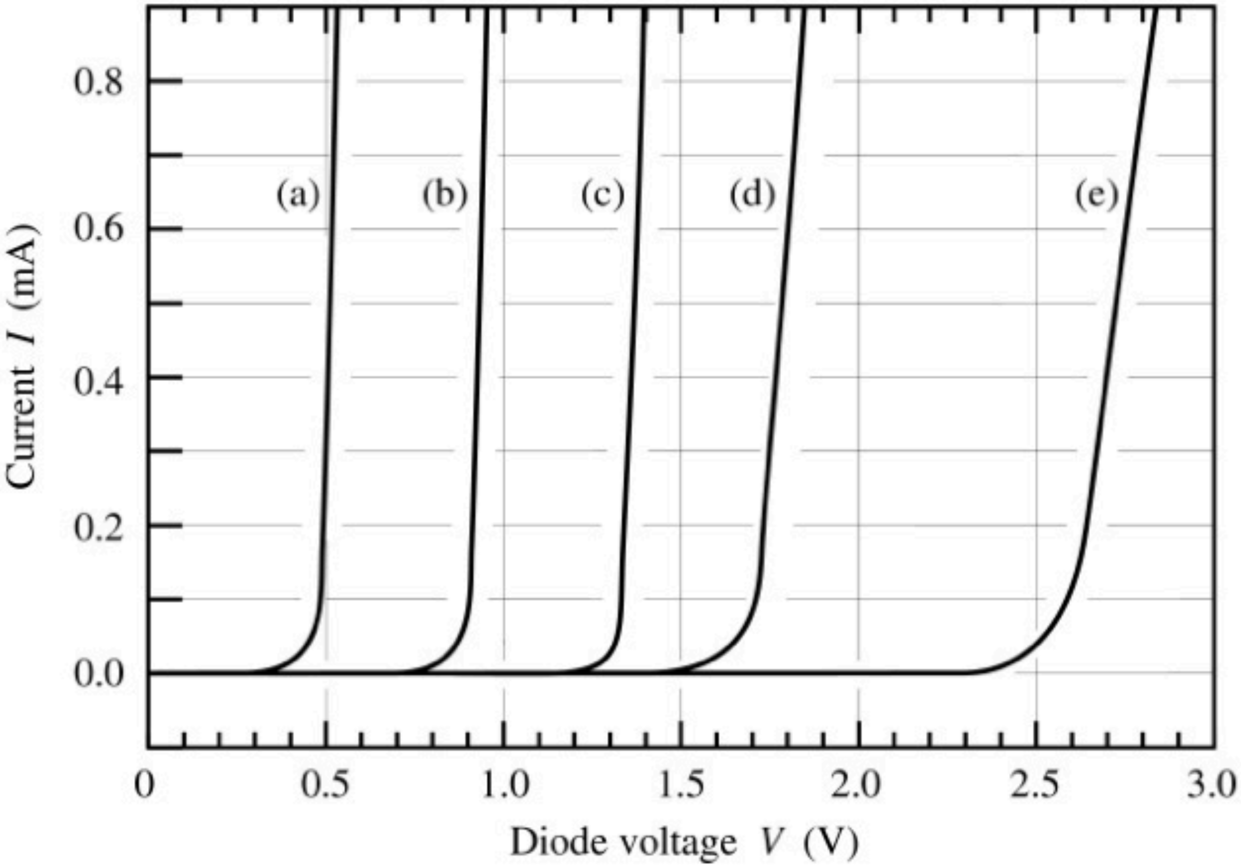


- Answer: double heterojunction LED! ☆

Emission is away from surface and surrounded by wider bandgap (transparent) semiconductor.

- Lastly, why p- for emitting layer? Think about defects and what they do to recombination…

Voltage Requirements



$T = 300$ K

(a)	Ge	$E_g \approx 0.7$ eV
(b)	Si	$E_g \approx 1.1$ eV
(c)	GaAs	$E_g \approx 1.4$ eV
(d)	GaAsP	$E_g \approx 2.0$ eV
(e)	GaInN	$E_g \approx 2.9$ eV

Fig. 4.2. Room temperature current - voltage characteristics of p-n junctions made of different semiconductors.

- Obviously, shorter wavelength emitters require a larger bandgap, and therefore have a larger turn-on voltage to overcome contact potential…

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How Efficient?

- Internal quantum efficiency ☆ (not heat, but photon emission!)

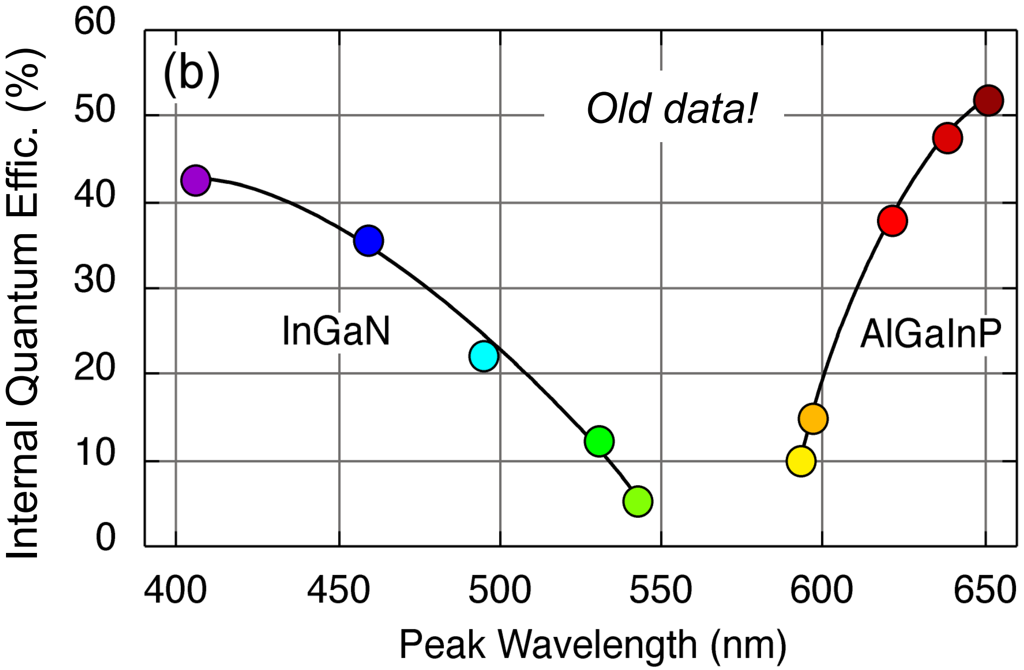
$$\eta_{int} = \frac{\textit{photons emitted}}{\textit{electrons injected}}$$

- Injection efficiency (recombine ☆ in the active region only, right E_g)

$$\gamma = \textit{\% electrons recombining in the active region}$$

- Outcoupling efficiency (next slide) ☆

$$\eta_{out} = \frac{\textit{photons escaping LED}}{\textit{photons generated inside}}$$



- *Internally* generated optical power for red LED with 1 mA?

$$P_{optical}(W) = (J/s) = (C/s)\times(J/C) = I \times 1240/\lambda(nm)\times\eta_{int}$$

$$P_{optical}(W) = 1\times10^{-3}\times1240/650\times(0.5)\approx 1mW$$

- Another way to calculate (get same answer). Red is about 2 eV. How much voltage to turn on the diode? What is the power consumed then? How *efficiently* is this power turned into photons?

Remember, not all of this optical power gets out! Lets calculate!

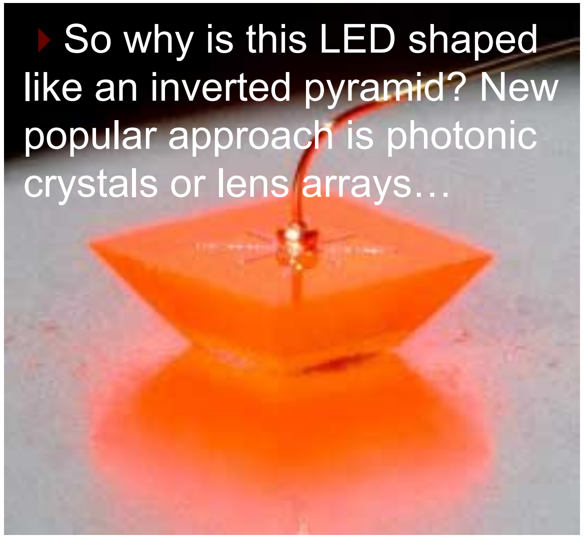
How Efficient?

- Lets calculate total external quantum efficiency (EQE) for an example GaP LED.

$$n_{ext} = \gamma \times n_{\text{int}} \times n_{out}$$

$$n_{ext} = 1 \times 0.5 \times 0.084 \approx 4\%$$

Why is out-coupling so poor?



- So why is this LED shaped like an inverted pyramid? New popular approach is photonic crystals or lens arrays…

(1) Fresnel reflection.

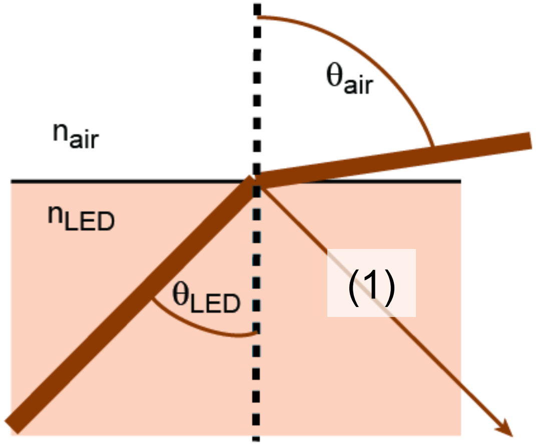
$$\% = \frac{(n_{LED} - n_{air})^2}{(n_{LED} + n_{air})^2}$$

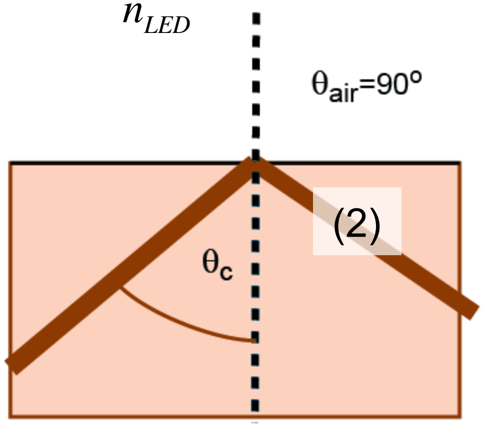
(2) Total internal reflection (TIR)

$$n_{LED} \sin\theta_{LED} = n_{air} \sin\theta_{air}$$

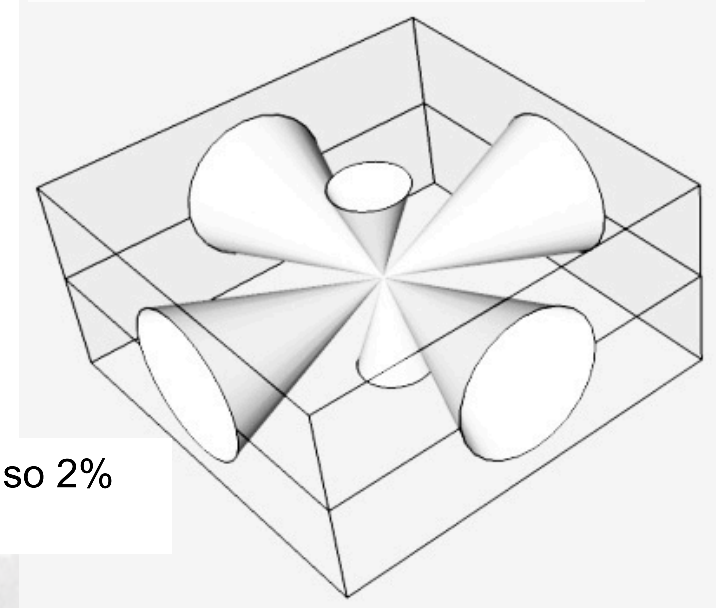
$$n_{LED} \sin\theta_C = n_{air} \sin 90$$

$$\theta_C = \sin^{-1} \frac{n_{air}}{n_{LED}}$$





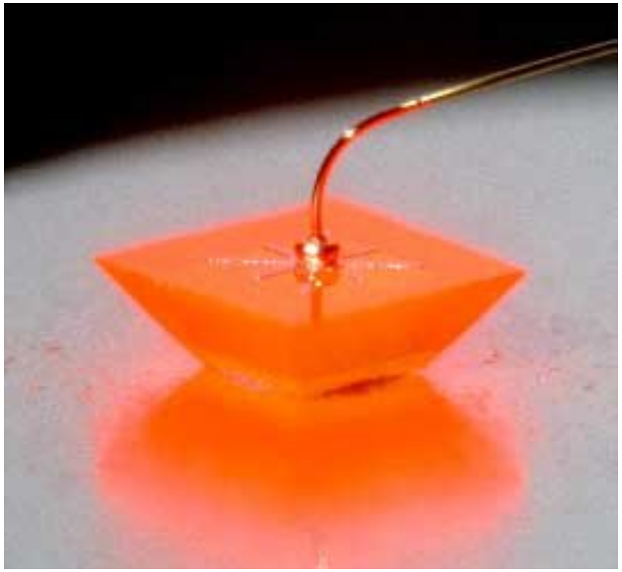
$$isotropic\ emit: each\ cone\ \% \approx 1/4n_{LED}^2$$



Example for GaP (n~3.4): Fresnel % = (1-0.3) or 70% out, θ_C=17° so 2% escapes at each of 6 sides) … 70% x 2% x 6 sides = 8.4%

Review! Take a Break!

- What type of semiconductors are typically used for LEDs? (where on periodic table).
- Why are green LEDs the hardest to make?
- Are the best LEDs just simple PN junctions (one material, homojunction)? Why or why not? Two reasons…
- What are the 3 key factors that effect LED efficiency?



Where we are headed…

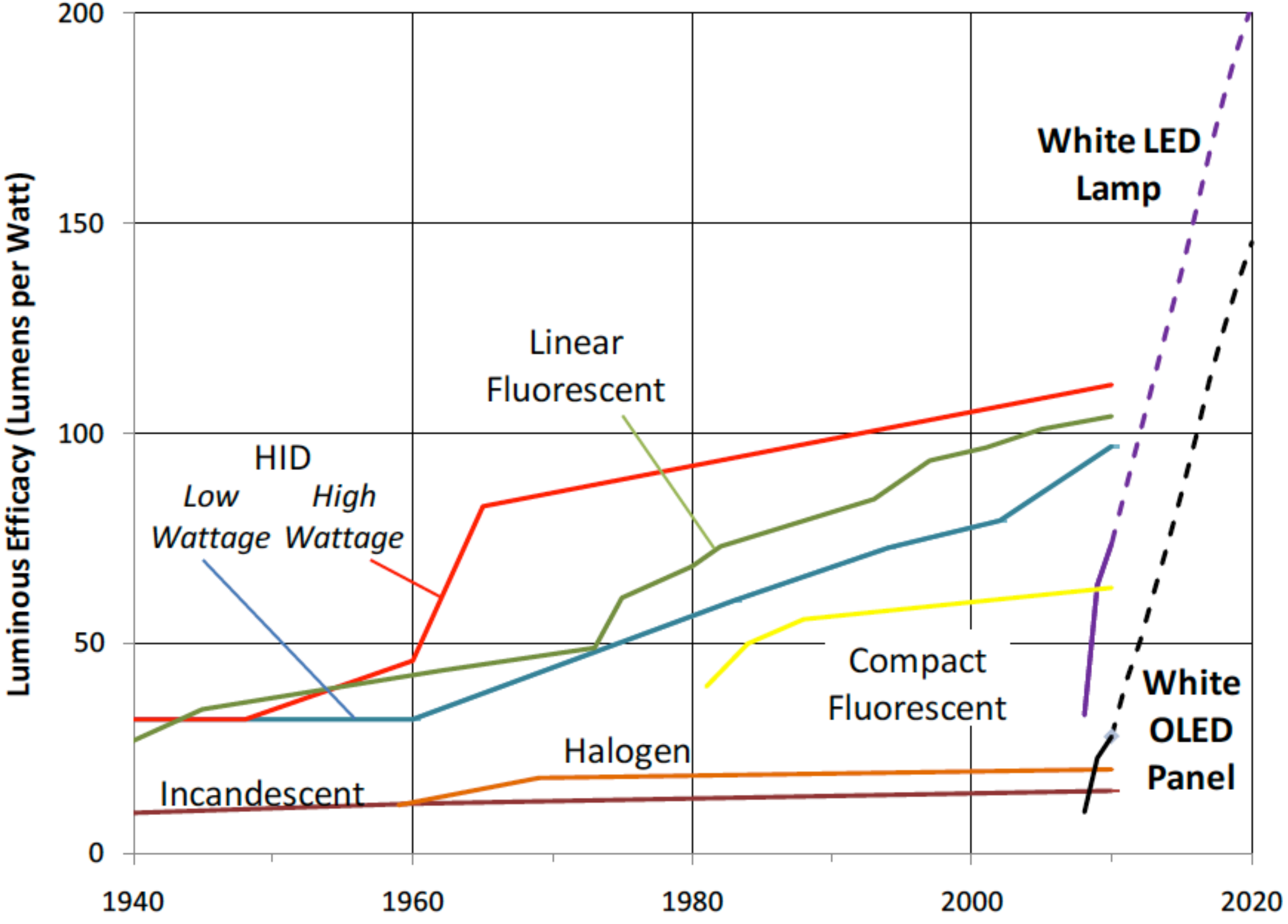


Figure 3.4: Historical and Predicted Efficacy of Light Sources[34]

Source: Navigant Consulting, Inc - Updated Lumileds' chart with data from product catalogues and press releases

Note: Efficacies for HID, fluorescent, and LED sources include driver or ballast losses.

What is lm/W?

- lm/W (lumen/W) takes into consideration the ‘brightness’ perceived by the human eye.

- If you have blue LEDs that are just as electrically efficient as a green LEDs, the blue LEDs still have lower luminous efficacy (looks dimmer).

- Is no mistake that the peak intensity of the sun is in the green…

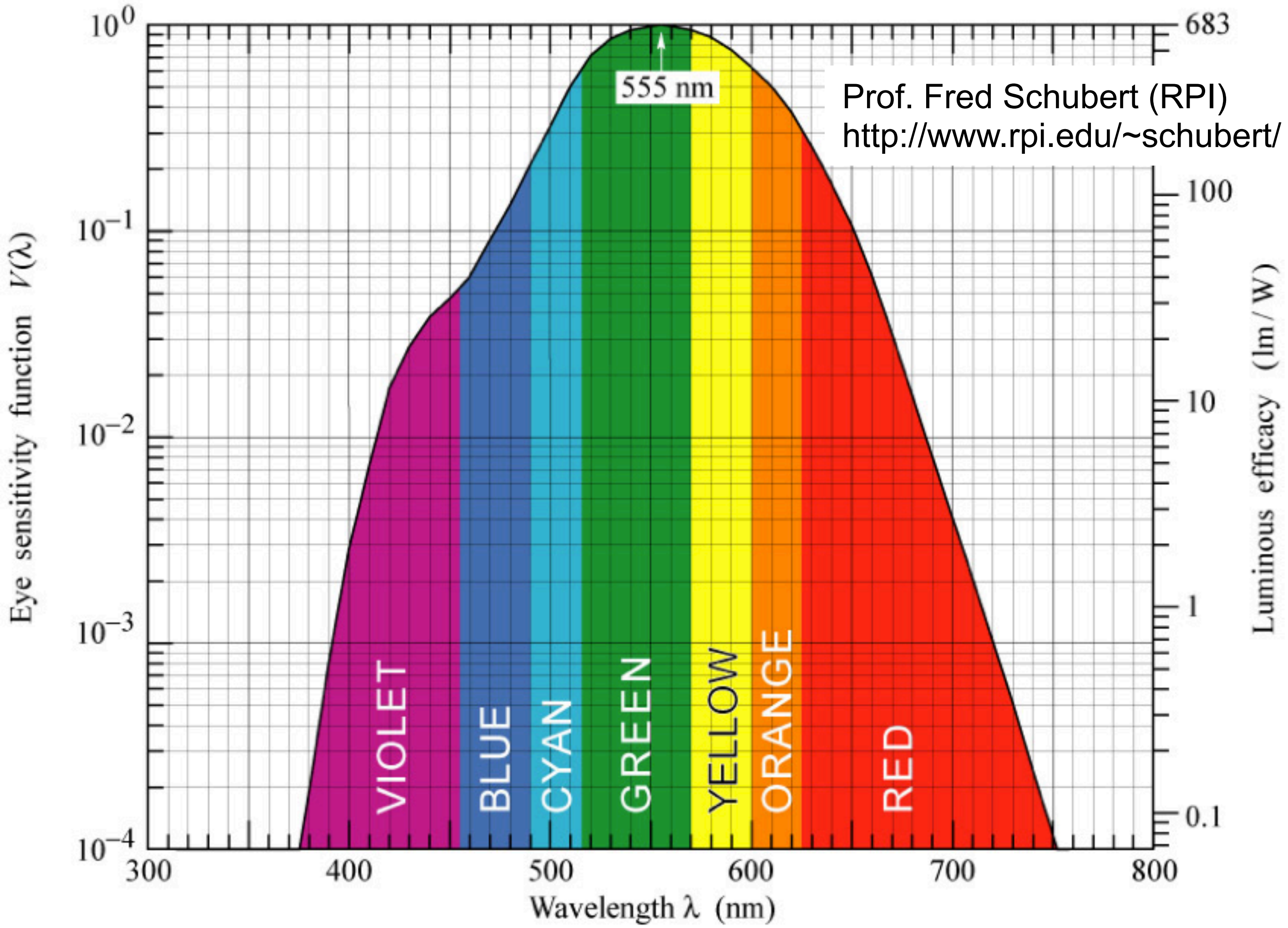


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Fig. 11.2. Eye sensitivity function, $V(\lambda)$, (left ordinate) and luminous efficacy, measured in lumens per Watt of optical power (right ordinate). The eye sensitivity is greatest at 555 nm. Also given is a polynomial approximation for $V(\lambda)$ (after 1978 CIE data).

How white LEDs are made…

- So, how do they make white LEDs? ☆

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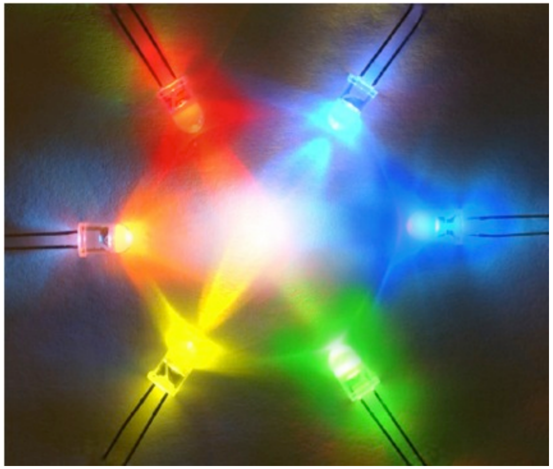


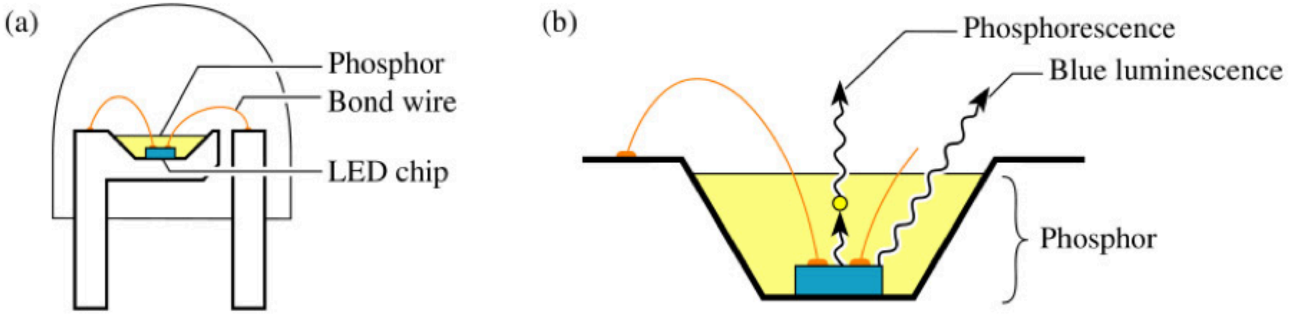
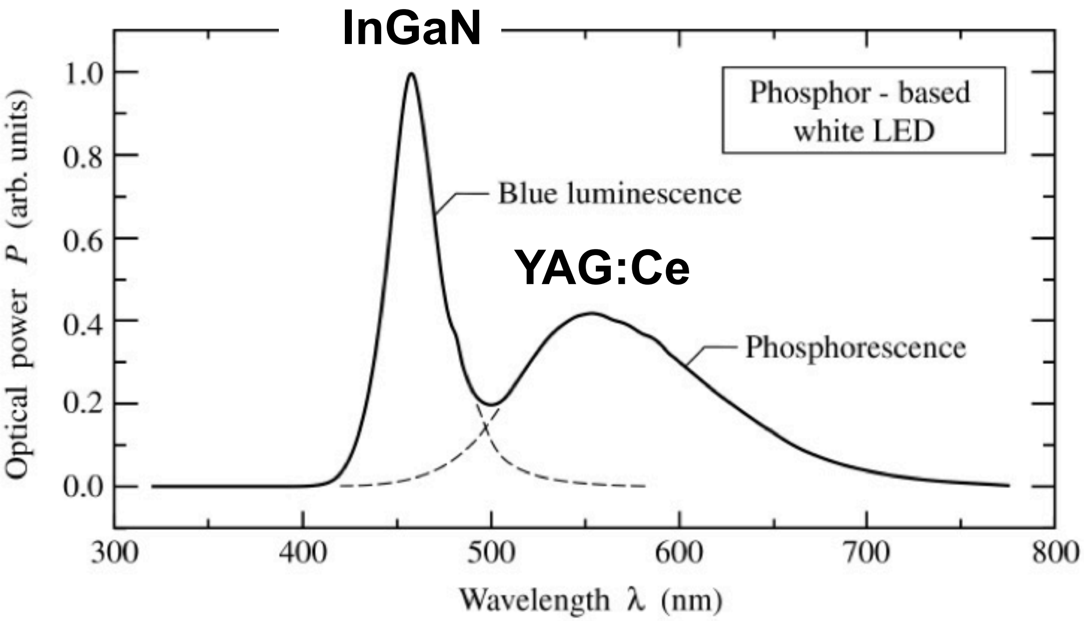


Fig. 12.5. (a) Structure of white LED consisting of a GaInN blue LED chip and a phosphor-containing epoxy encapsulating the semiconductor die. (b) Wavelength-converting phosphorescence and blue luminescence (after Nakamura and Fasol, 1997).

Cree XR-E

- So, your local art museum switches to these type of white LEDs and the patrons say all the art looks terrible (colors are off a bit). Why? How fix?



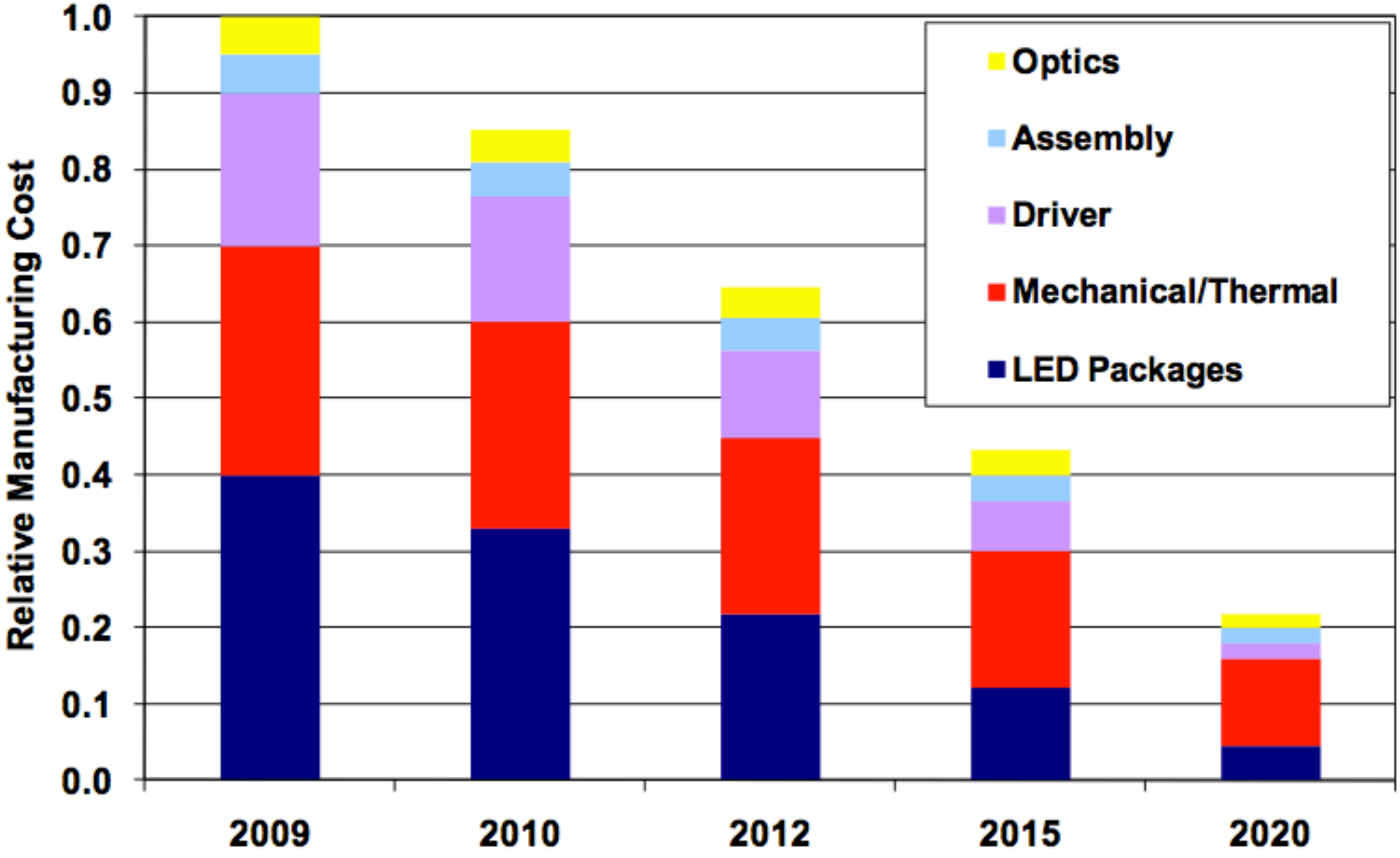
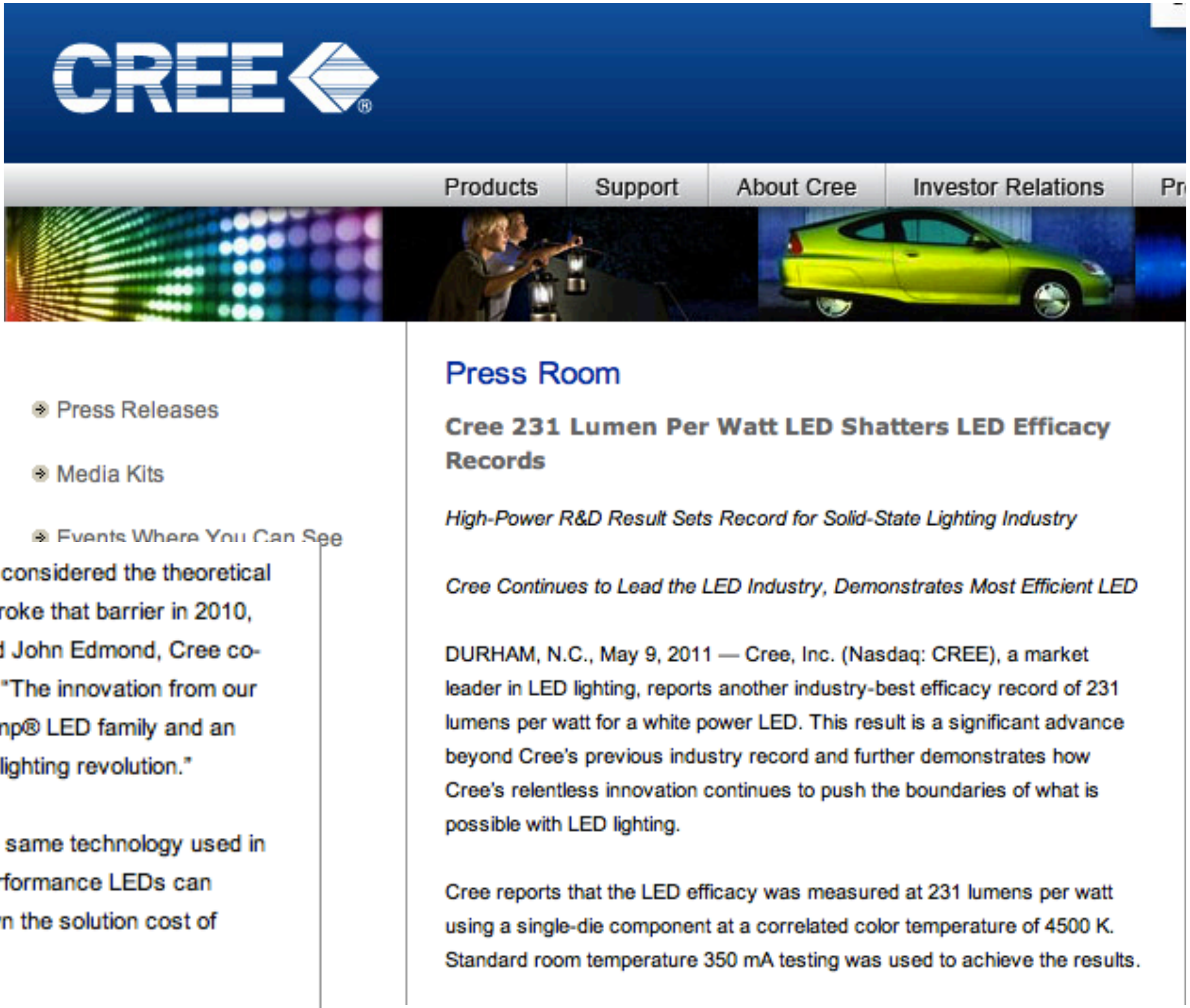


Figure 1. Projected LED Luminaire Cost Track
Source: DOE Manufacturing Workshop consensus



Press Room

Cree 231 Lumen Per Watt LED Shatters LED Efficacy Records

High-Power R&D Result Sets Record for Solid-State Lighting Industry

Cree Continues to Lead the LED Industry, Demonstrates Most Efficient LED

DURHAM, N.C., May 9, 2011 — Cree, Inc. (Nasdaq: CREE), a market leader in LED lighting, reports another industry-best efficacy record of 231 lumens per watt for a white power LED. This result is a significant advance beyond Cree's previous industry record and further demonstrates how Cree's relentless innovation continues to push the boundaries of what is possible with LED lighting.

Cree reports that the LED efficacy was measured at 231 lumens per watt using a single-die component at a correlated color temperature of 4500 K. Standard room temperature 350 mA testing was used to achieve the results.

"It wasn't long ago when 200 lumens per watt was considered the theoretical maximum efficiency for a lighting-class LED. We broke that barrier in 2010, and have now achieved 231 lumens per watt," said John Edmond, Cree co-founder and director of advanced optoelectronics. "The innovation from our labs is the foundation for our industry-leading XLamp® LED family and an invention that continues our leadership of the LED lighting revolution."

This R&D result features advanced aspects of the same technology used in Cree XLamp white LEDs. Cree believes higher-performance LEDs can enable new LED-based applications and drive down the solution cost of current LED-based designs.

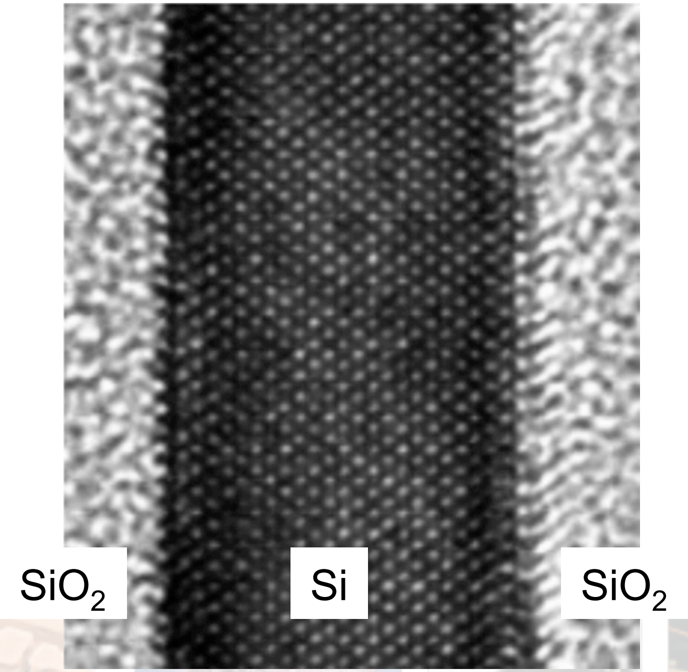
While this level of performance is not yet available in Cree's production LEDs, Cree continues to lead the industry with the broadest family of high-performance LEDs.

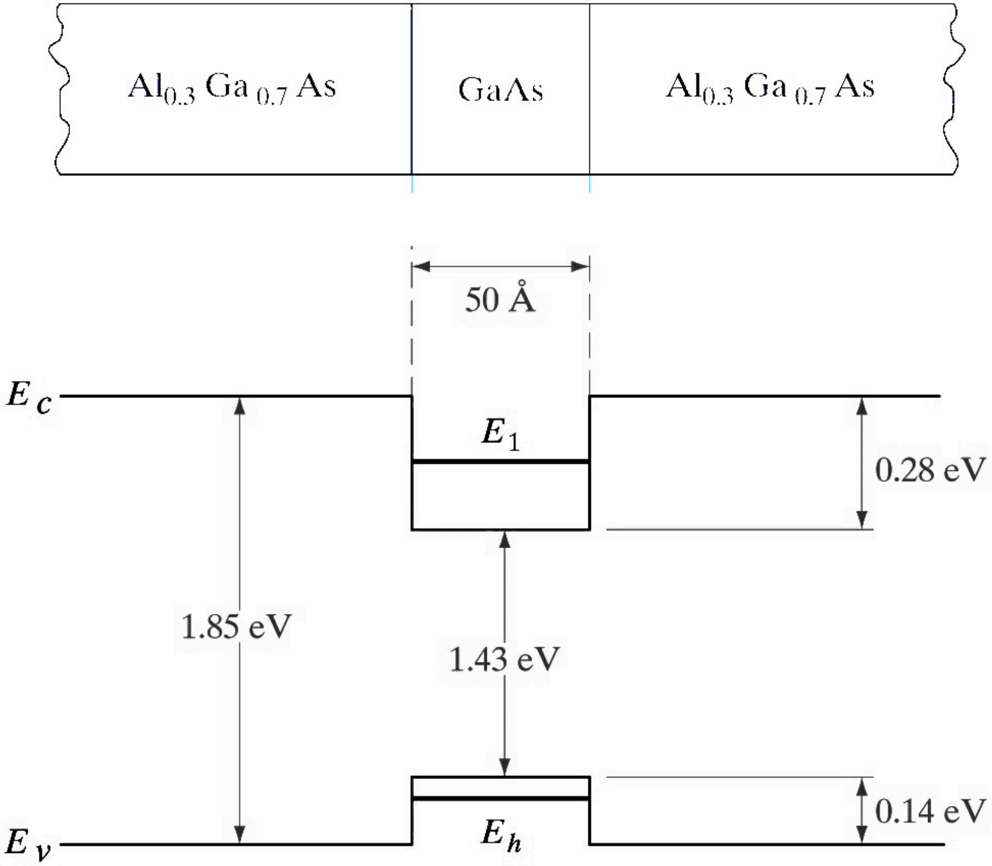
Quantum Wells

- We can also tune emission wavelengths through quantum confinement!

- Energy levels for an infinitely deep quantum well (one at right is finite, but lower states are similar).

$$E_n = \frac{h^2}{2m^*}\left(\frac{n}{2L}\right)^2 \qquad n = 1,2\ldots$$

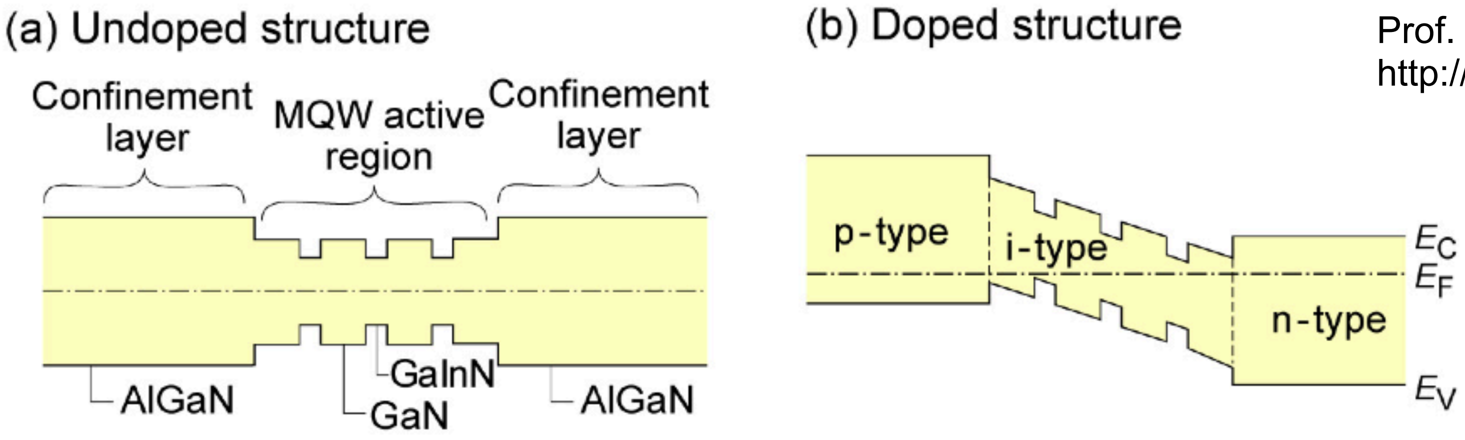




$$V = \frac{E_{photon}}{q} + I \times R_S + \frac{\Delta E_C}{q} + \frac{\Delta E_V}{q}$$

Quantum Wells

- Quantum Wells in some cases allow higher efficiency because: (1) promote a higher radiative efficiency; (2) trap carriers so less surface recombination (like DH LED).



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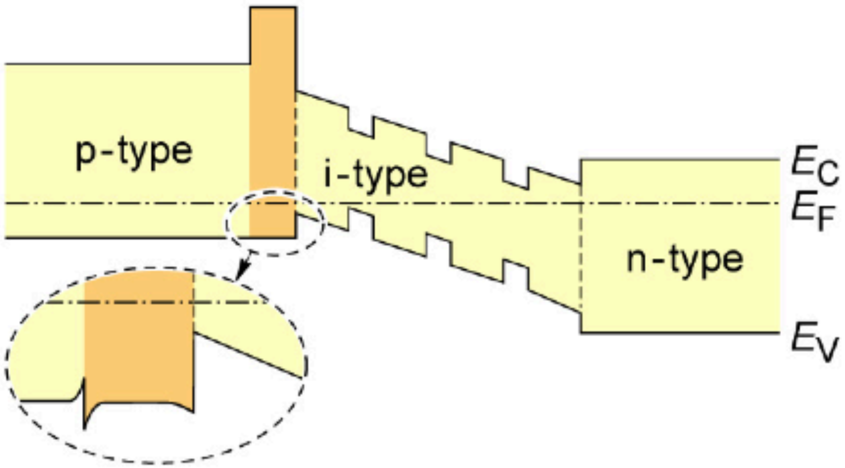
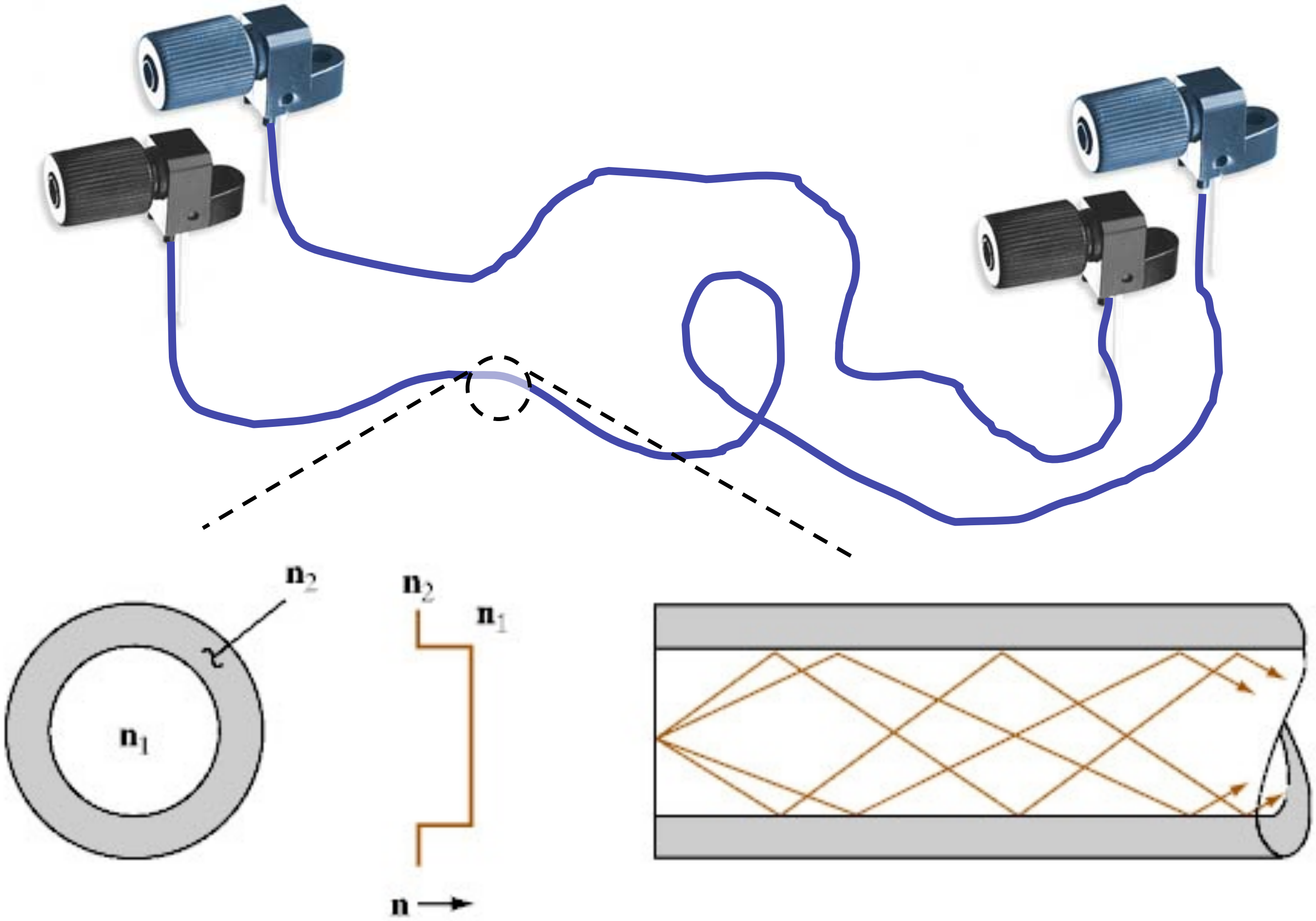
- Even better, add in electron and hole blocking layers (bandgap and doping).



LEDs in communication

- LED (electro/opto) …
011010100101…



- Photodiode (opto/electro) …
011010100101…

LEDs in communication

- LEDs are used for short-distance communications…

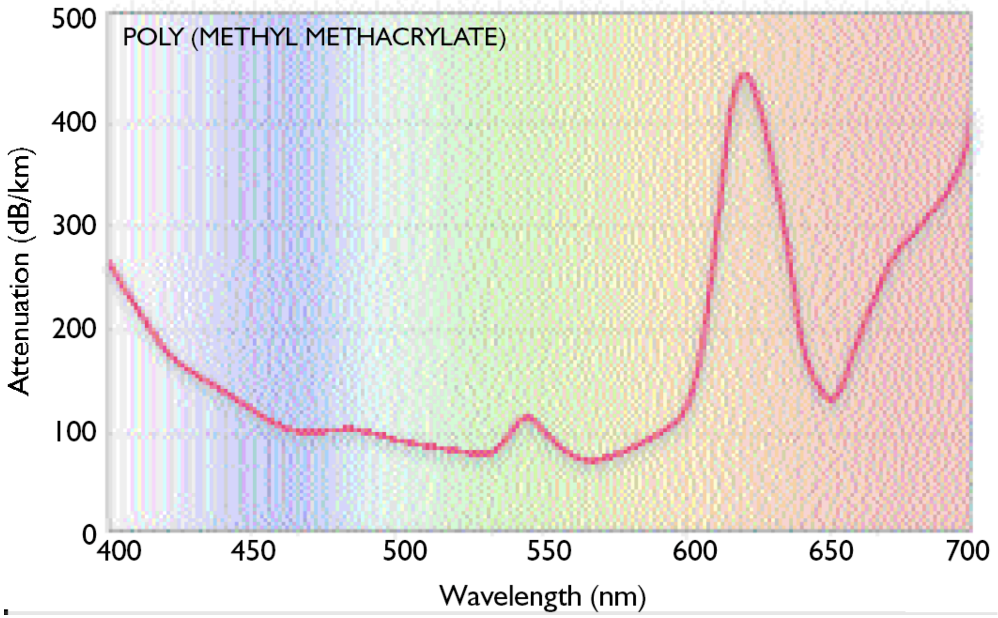
- Even 100 dB/km is a lot of loss!

$$\alpha(dB/km) = \frac{-10\log(P_z/P_0)}{z}$$

$$if\ \frac{P_z}{P_0} = 0.10, \alpha = 100$$

$$then\ z = 0.1\ km \quad (100m)$$

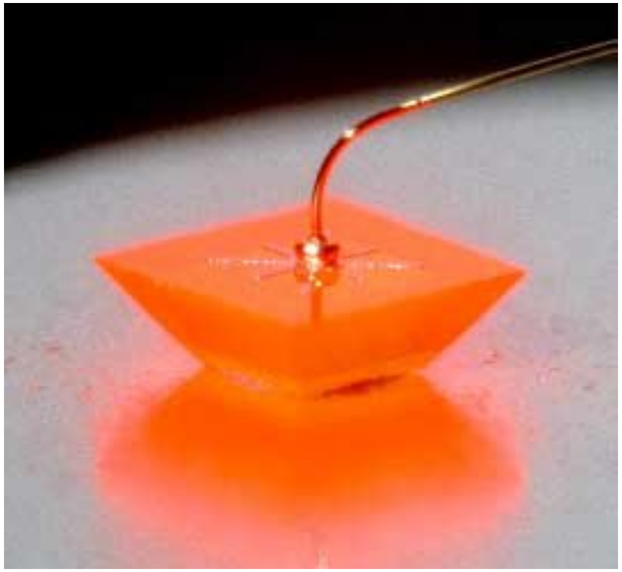
☆



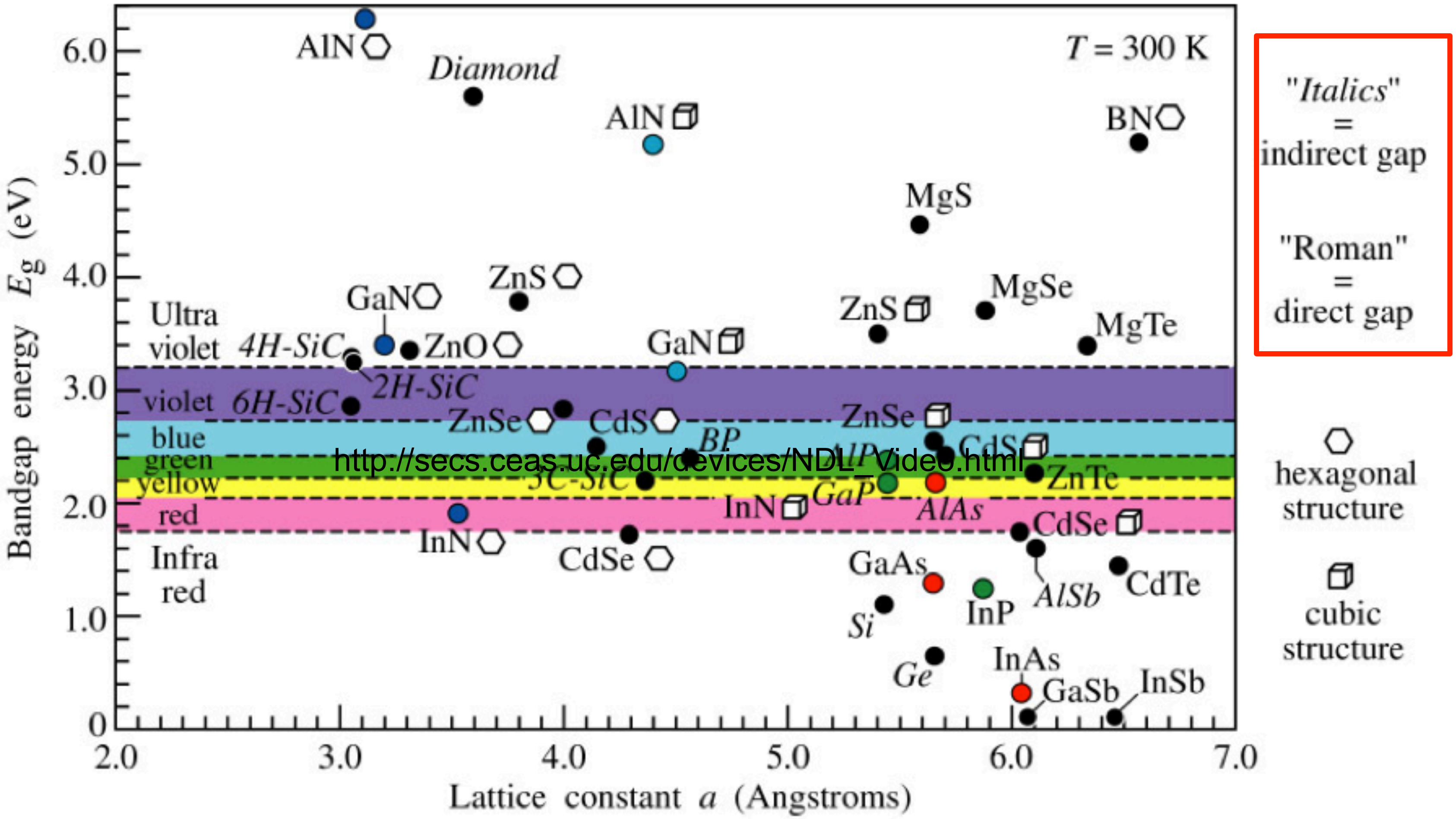
- Good for cars, stereos, industrial controls, etc… but NOT for the internet (transoceanic, etc.). We will learn more about that when we cover LASERS!

Review!

- How do we make white LEDs?
- What is lm/W?
- LEDs are used for what type of optical communication?
- What is a good U.S. company to work for in LED technology?



Which Semicon used for LEDs?



http://secs.ceas.uc.edu/devices/NDL_Video.html

Fig. 12.4. Room-temperature bandgap energy versus lattice constant of common elemental and binary compound semiconductors.

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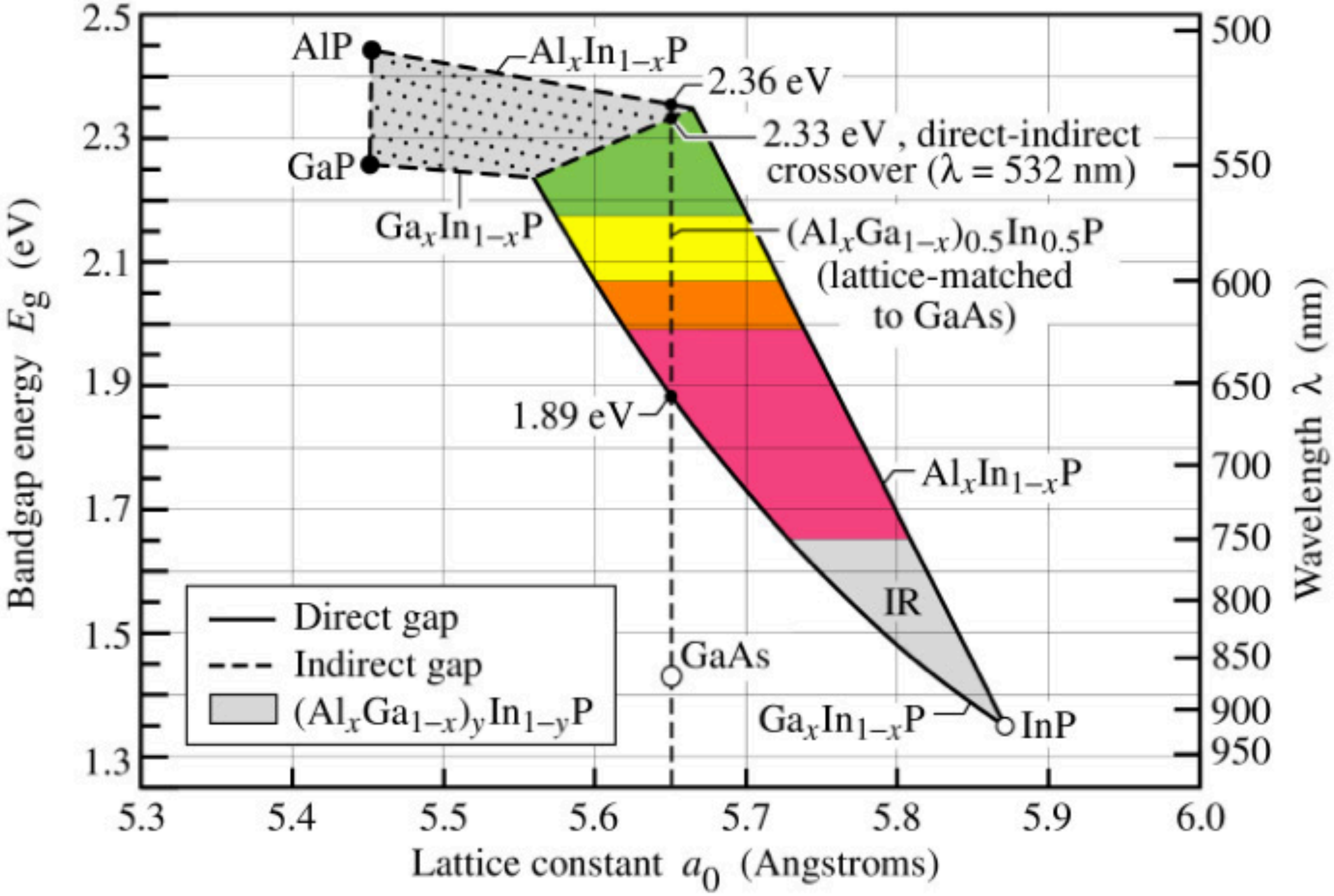
Which Semicon used for LEDs?



AlP
$E_g = 2.45$ eV
$a_0 = 5.4510$ Å

GaP
$E_g = 2.26$ eV
$a_0 = 5.4512$ Å

InP
$E_g = 1.35$ eV
$a_0 = 5.8686$ Å

GaAs
$E_g = 1.424$ eV
$a_0 = 5.6533$ Å

Fig. 8.9. Bandgap energy and corresponding wavelength versus lattice constant of $(Al_xGa_{1-x})_yIn_{1-y}P$ at 300 K. The dashed vertical line shows $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ lattice matched to GaAs (adopted from Chen *et al.*, 1997).

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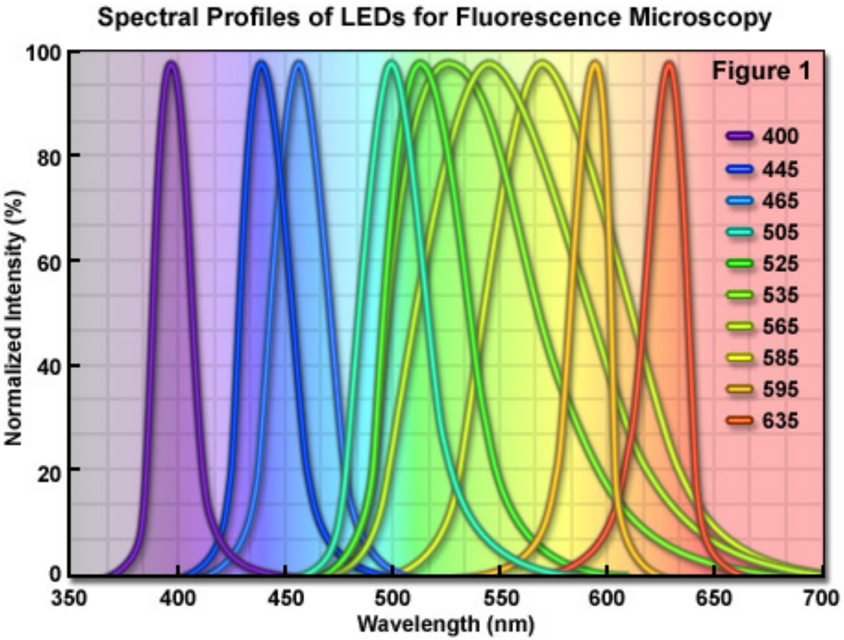
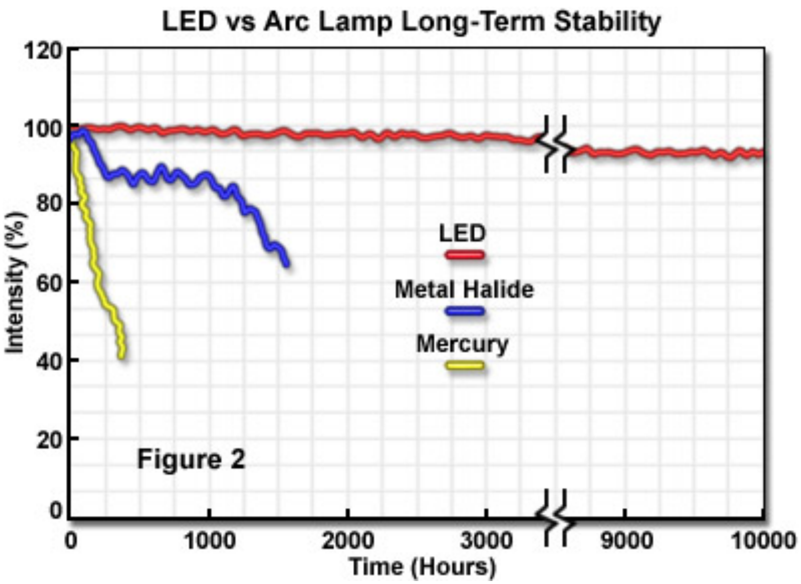
http://www.rpi.edu/~schubert/

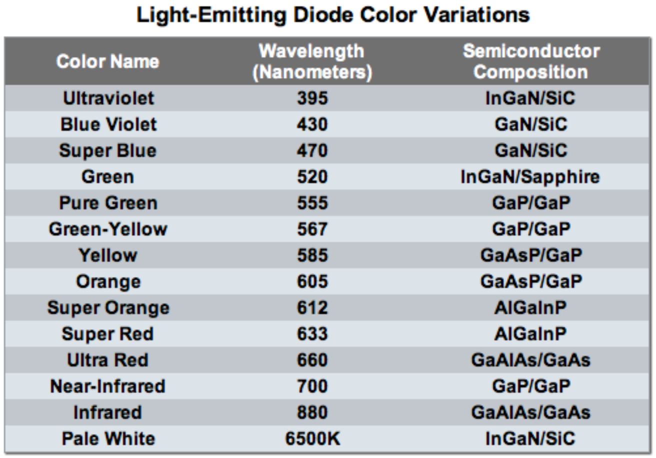
Some more info (from Zeiss)



Spectral Profiles of LEDs for Fluorescence Microscopy

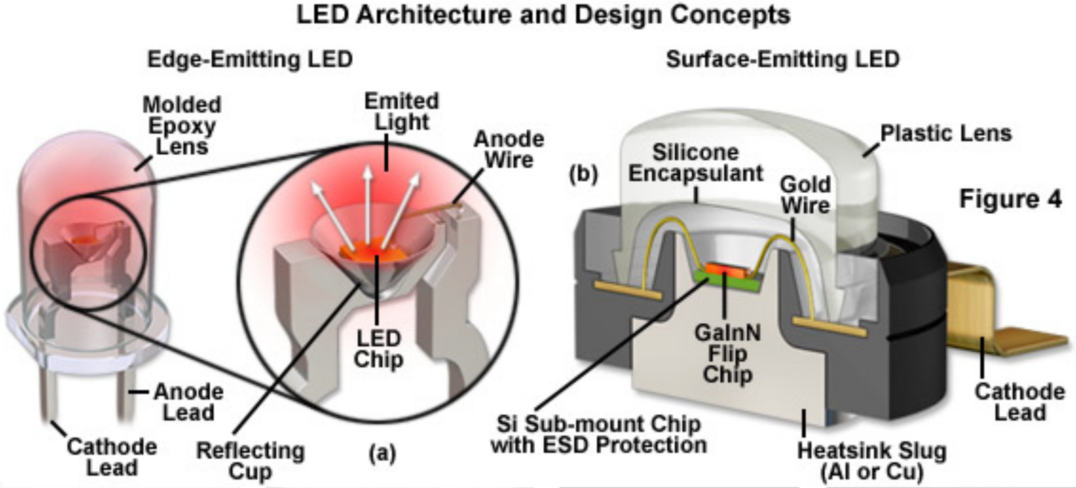


LED vs Arc Lamp Long-Term Stability



Light-Emitting Diode Color Variations

Color Name	Wavelength (Nanometers)	Semiconductor Composition
Ultraviolet	395	InGaN/SiC
Blue Violet	430	GaN/SiC
Super Blue	470	GaN/SiC
Green	520	InGaN/Sapphire
Pure Green	555	GaP/GaP
Green-Yellow	567	GaP/GaP
Yellow	585	GaAsP/GaP
Orange	605	GaAsP/GaP
Super Orange	612	AlGaInP
Super Red	633	AlGaInP
Ultra Red	660	GaAlAs/GaAs
Near-Infrared	700	GaP/GaP
Infrared	880	GaAlAs/GaAs
Pale White	6500K	InGaN/SiC



LED Architecture and Design Concepts

Where we are headed…

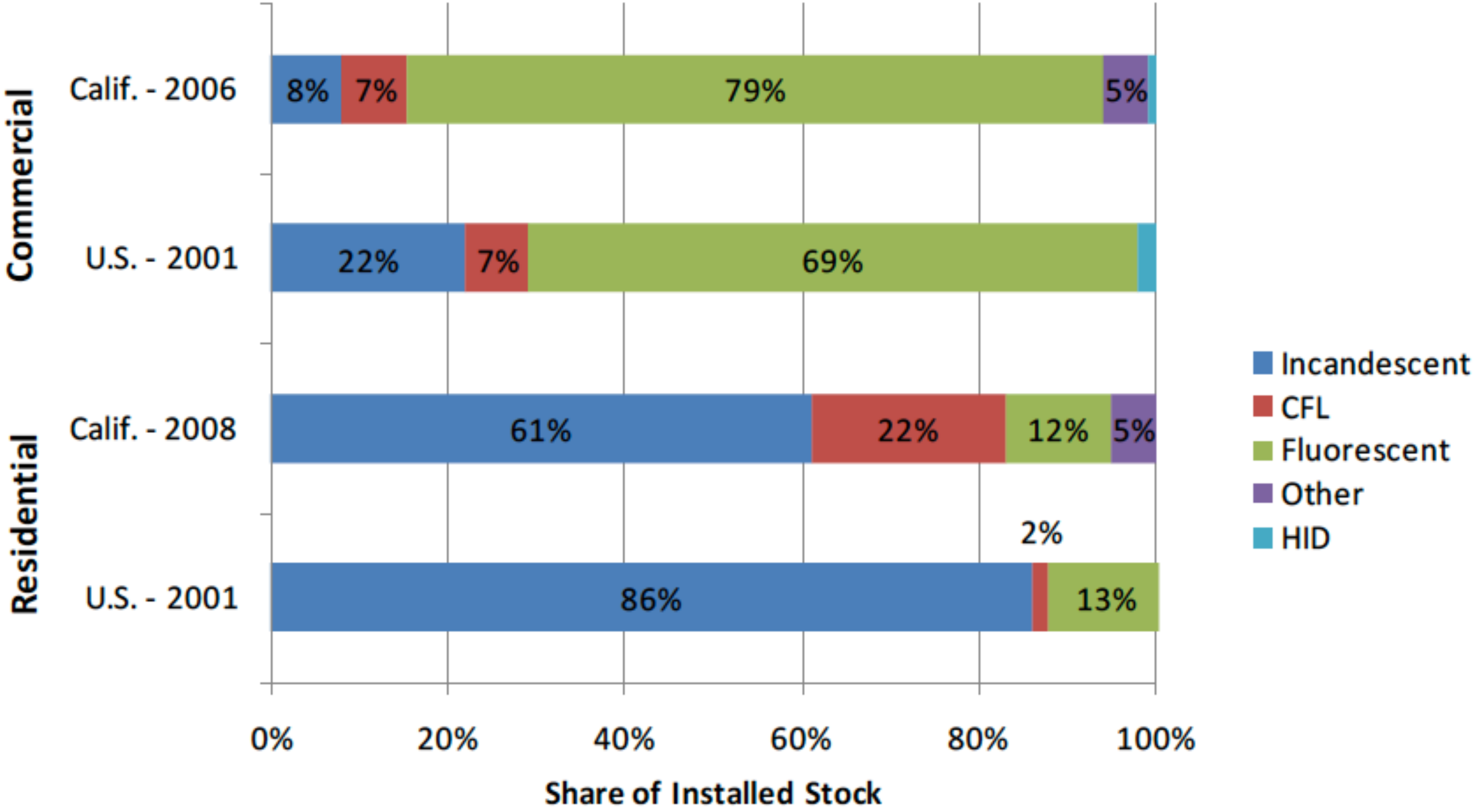


Figure 2.1: Estimate of the U.S. Installed Stock of Lamps (based on California data)
Sources: Residential – Final Evaluation Report: Upstream Lighting Program, CPUC
Commercial – California Commercial End-Use Survey, CEC

Where we are headed…

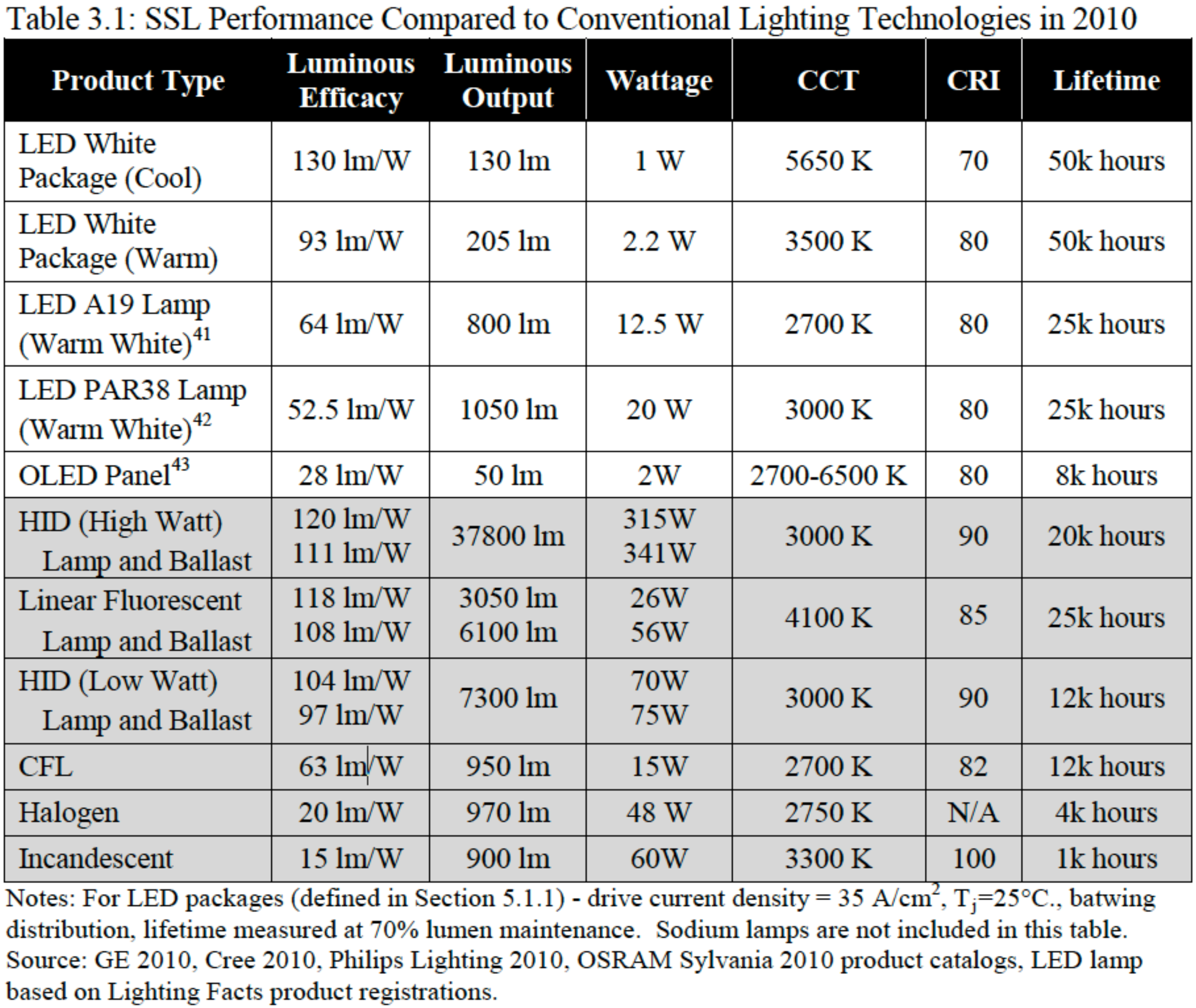


Table 3.1: SSL Performance Compared to Conventional Lighting Technologies in 2010

Product Type	Luminous Efficacy	Luminous Output	Wattage	CCT	CRI	Lifetime
LED White Package (Cool)	130 lm/W	130 lm	1 W	5650 K	70	50k hours
LED White Package (Warm)	93 lm/W	205 lm	2.2 W	3500 K	80	50k hours
LED A19 Lamp (Warm White)[41]	64 lm/W	800 lm	12.5 W	2700 K	80	25k hours
LED PAR38 Lamp (Warm White)[42]	52.5 lm/W	1050 lm	20 W	3000 K	80	25k hours
OLED Panel[43]	28 lm/W	50 lm	2W	2700-6500 K	80	8k hours
HID (High Watt) Lamp and Ballast	120 lm/W 111 lm/W	37800 lm	315W 341W	3000 K	90	20k hours
Linear Fluorescent Lamp and Ballast	118 lm/W 108 lm/W	3050 lm 6100 lm	26W 56W	4100 K	85	25k hours
HID (Low Watt) Lamp and Ballast	104 lm/W 97 lm/W	7300 lm	70W 75W	3000 K	90	12k hours
CFL	63 lm/W	950 lm	15W	2700 K	82	12k hours
Halogen	20 lm/W	970 lm	48 W	2750 K	N/A	4k hours
Incandescent	15 lm/W	900 lm	60W	3300 K	100	1k hours

Notes: For LED packages (defined in Section 5.1.1) - drive current density = 35 A/cm^2, T_j=25°C., batwing distribution, lifetime measured at 70% lumen maintenance. Sodium lamps are not included in this table. Source: GE 2010, Cree 2010, Philips Lighting 2010, OSRAM Sylvania 2010 product catalogs, LED lamp based on Lighting Facts product registrations.

Where we are headed…

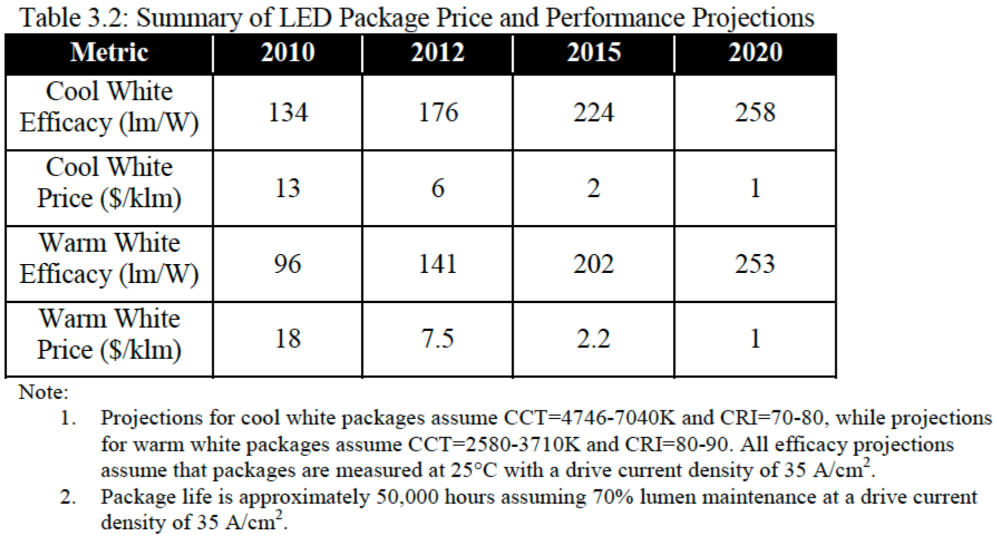


Table 3.2: Summary of LED Package Price and Performance Projections

Metric	2010	2012	2015	2020
Cool White Efficacy (lm/W)	134	176	224	258
Cool White Price ($/klm)	13	6	2	1
Warm White Efficacy (lm/W)	96	141	202	253
Warm White Price ($/klm)	18	7.5	2.2	1

Note:

1. Projections for cool white packages assume CCT=4746-7040K and CRI=70-80, while projections for warm white packages assume CCT=2580-3710K and CRI=80-90. All efficacy projections assume that packages are measured at 25°C with a drive current density of 35 A/cm^2.
2. Package life is approximately 50,000 hours assuming 70% lumen maintenance at a drive current density of 35 A/cm^2.

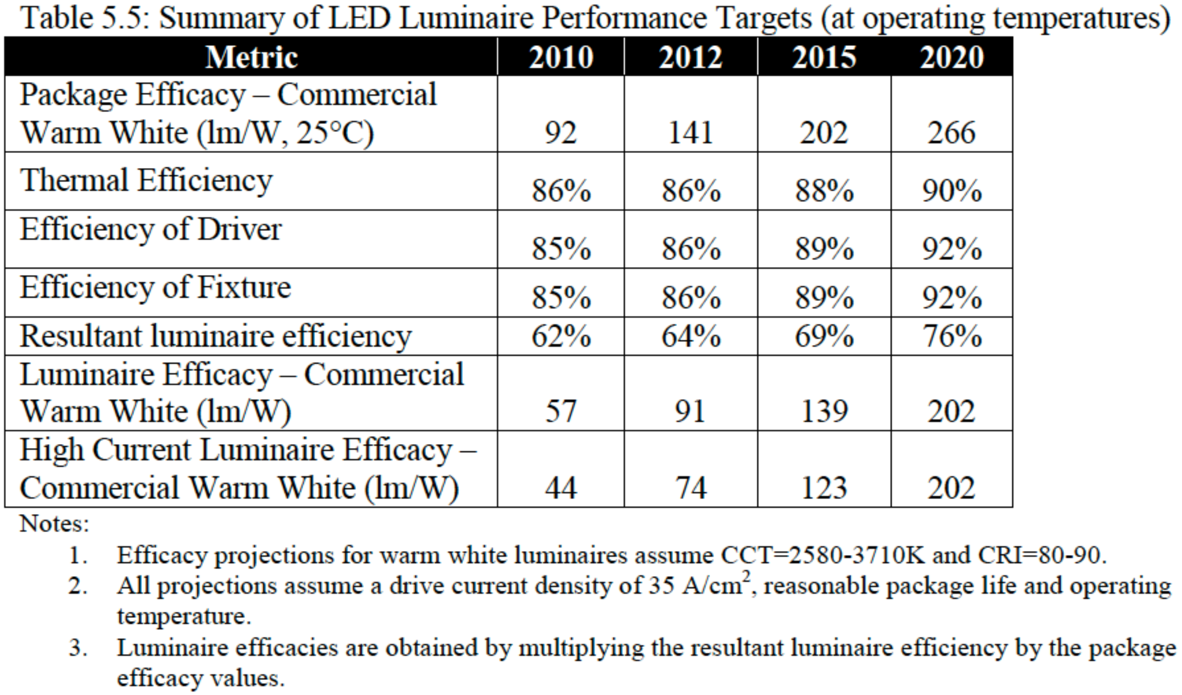


Table 5.5: Summary of LED Luminaire Performance Targets (at operating temperatures)

Metric	2010	2012	2015	2020
Package Efficacy – Commercial Warm White (lm/W, 25°C)	92	141	202	266
Thermal Efficiency	86%	86%	88%	90%
Efficiency of Driver	85%	86%	89%	92%
Efficiency of Fixture	85%	86%	89%	92%
Resultant luminaire efficiency	62%	64%	69%	76%
Luminaire Efficacy – Commercial Warm White (lm/W)	57	91	139	202
High Current Luminaire Efficacy – Commercial Warm White (lm/W)	44	74	123	202

Notes:

1. Efficacy projections for warm white luminaires assume CCT=2580-3710K and CRI=80-90.
2. All projections assume a drive current density of 35 A/cm^2, reasonable package life and operating temperature.
3. Luminaire efficacies are obtained by multiplying the resultant luminaire efficiency by the package efficacy values.

CREE®

XLamp® XM-L LED

Features

Delivers 1000 lumens at 100 lumens/W
Low thermal resistance: 2.5°C/W
ANSI-compatible chromaticity bins
Unlimited floor life at ≤ 30ºC/85% RH
Reflow solderable - JEDEC J-STD-020C
Electrically neutral thermal path

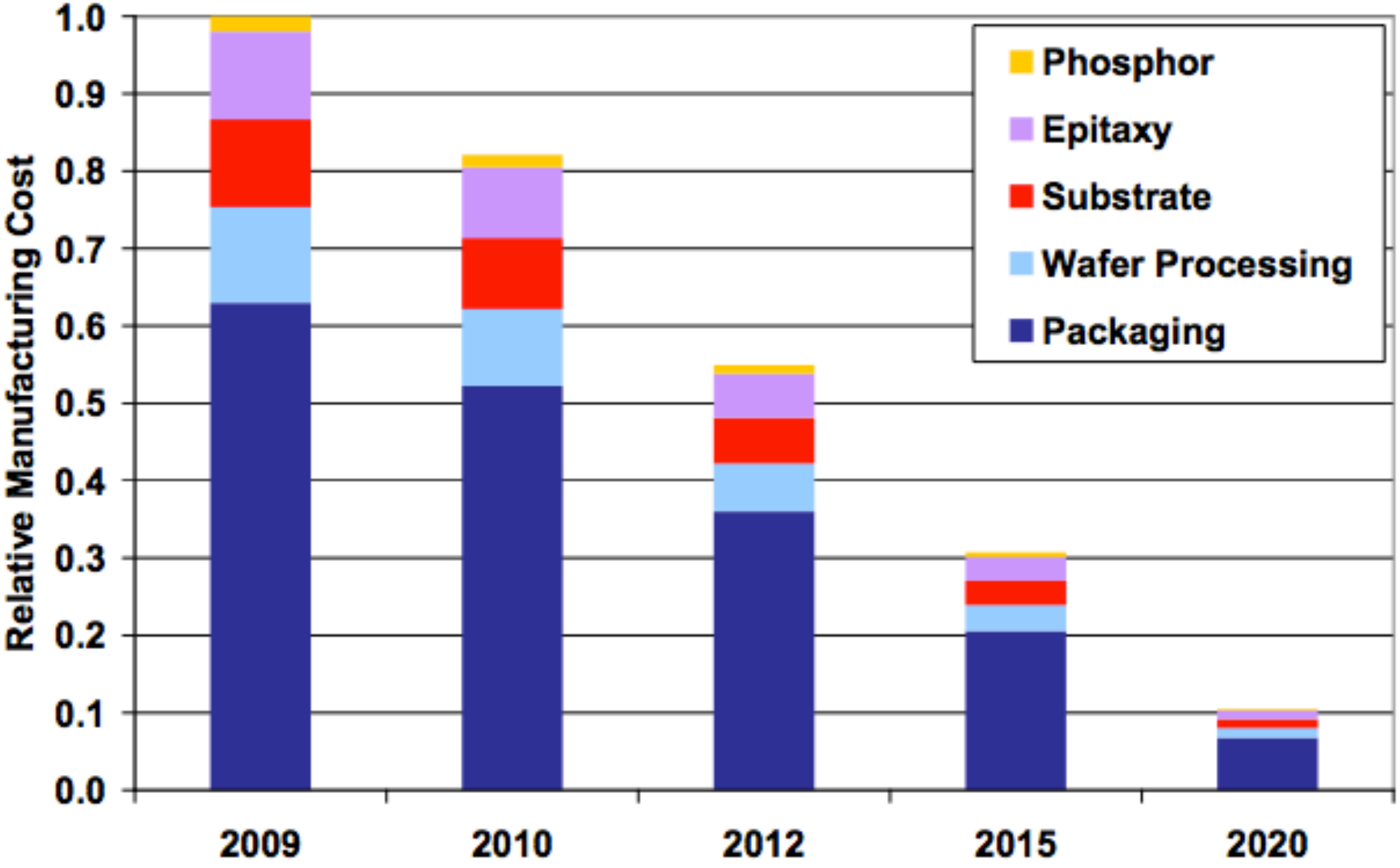


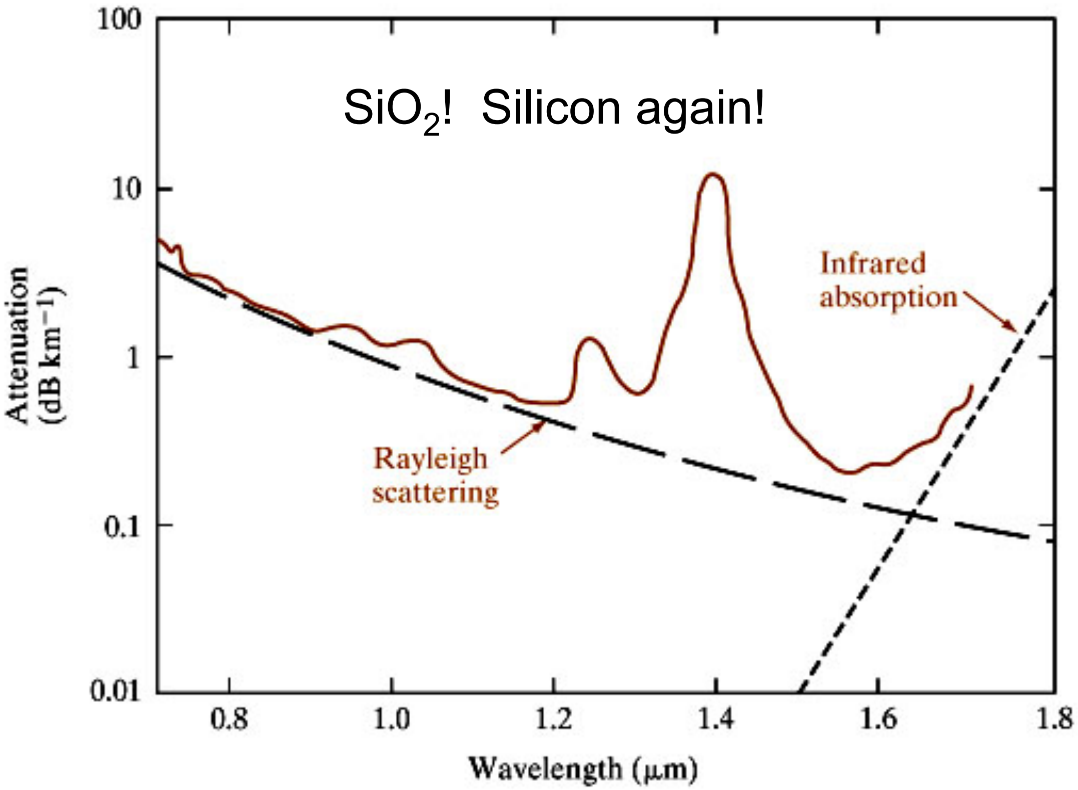
Figure 2. Projected LED Package Cost Track.
Source: Preliminary data provided by the Cost Modeling Working Group

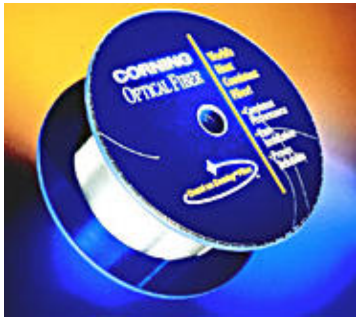
LEDs for long distance? No…

$$\alpha(dB/km) = \frac{-10\log(P_z/P_0)}{z} \qquad if\ \frac{P_z}{P_0} = 0.10,\ \alpha = 0.3$$

$$then\ z = 30{,}000m \quad (30\,km)$$

SiO$_2$! Silicon again!





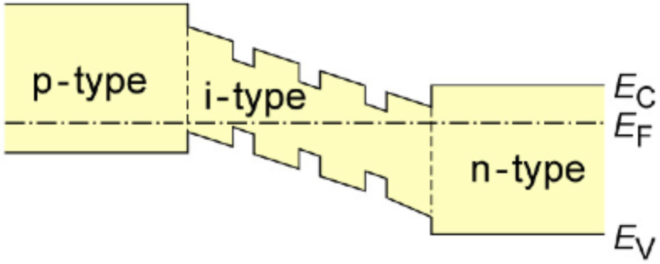
Why lasers?
(1) Coherent, so can use external modulator. (2) Low dispersion.

- Copper wire: 100 Mbps over 100 m
- LEDs / POF: 10 Gbps over 100 m
- Lasers / Glass Fiber: 40 Gbps over 1000’s of m !!

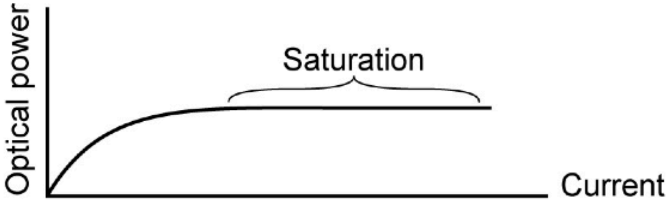
We will talk about lasers next time….

Quantum Wells

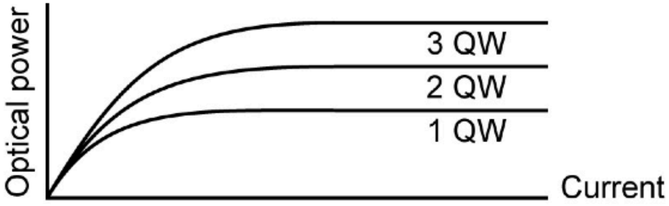
- Why multiple quantum wells (MQW)?



Light output characteristic of SQW LED:



Solution: MQW structures:



Prof. Fred Schubert (RPI)
http://www.rpi.edu/~schubert/

Semiconductor Today 25 September 2007

LED makers report progress at ICNS

…

Lumileds' solution is to instead use a double heterostructure (DH), which can have an electron-hole recombination region of over 6nm, compared to just 1nm for an MQW-based LED. The result is that, although quantum efficiency is lower, its peak is shifted to higher current density. So, for example for an encapsulated flip-chip LED with a 1mm x 1mm chip emitting at a wavelength of 444nm, a 9nm DH LED has higher quantum efficiency above a current density of 100A/cm² than an MQW LED with two 2.5nm quantum wells.