LED Replacements: Efficacy for Toledo's Streetlamps

Paul R. Berger
Department of Electrical and Computer Engineering
Department of Physics
The Ohio State University
Columbus OH, USA 43210

THE OHIO STATE UNIVERSITY

Current Landscape of Street lighting

Sodium Lamp

High lumen output at high efficiency *(1920 - Today)*

http://www.edisontechcenter.org/SodiumLamps.html

An HPS lamp with a starting strip, it uses a xenon starting gas.

Statistics:
CRI 20-30
80-140 lumens per watt
Bulb Life: 24,000 hrs
(8 yrs @ 8 hrs/night)

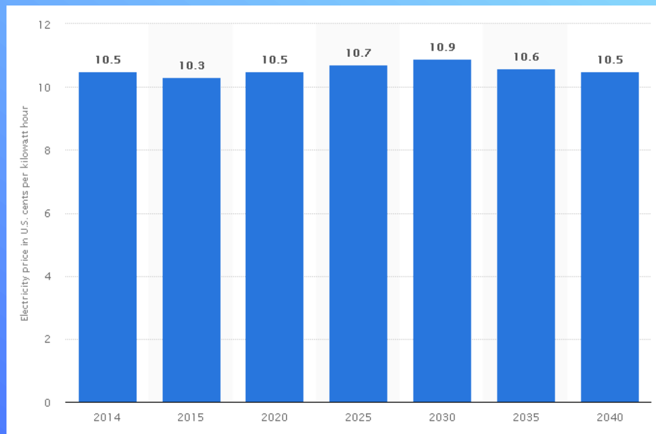
Advantages:
-Good efficiency (lumens per watt)
-Smaller size than LPS or fluorescent, the HPS fits into many fixture types
-Can be retrofitted into older Mercury Vapor fixtures
-Better bulb life than LPS lamps

Disadvantages:
- Worst color rendering of any lamp
- Sodium is a hazardous material which can combust when exposed to air (such as if the bulb is broken in the trash)
- Requires a lossy ballast (inefficient) that operates a low arc voltage of 52-100V. This reduces the actual efficiency of the lamp when you count the whole system together.

THE OHIO STATE UNIVERSITY

Cost of Energy Forecast

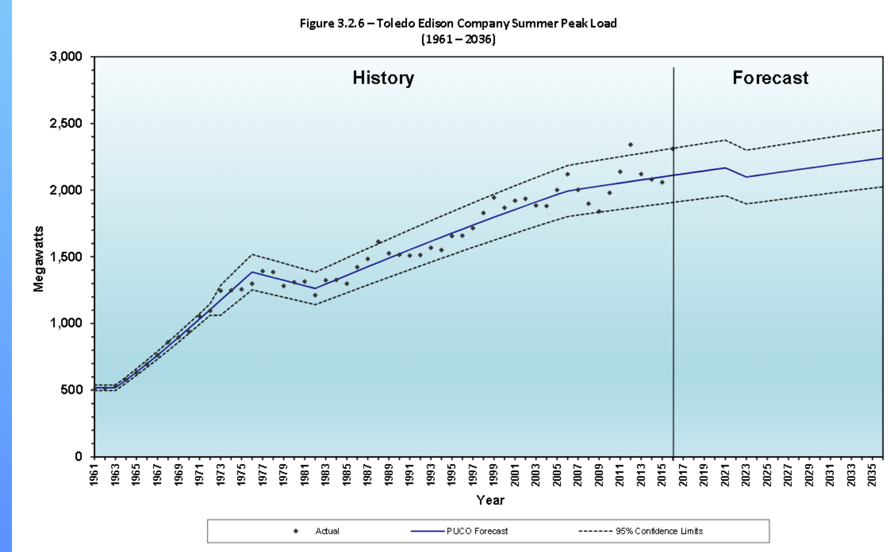
Projection of average end-use electricity price in the U.S. from 2014 to 2040 (in U.S. cents per kilowatt hour)



https://www.statista.com/statistics/630136/projection-of-electricity-prices-in-the-us/

Ohio Long-Term Forecast of Energy Requirements 2017-2036
A report by the staff of the Public Utilities Commission of Ohio
May 7, 2018

Toledo Edison Forecast

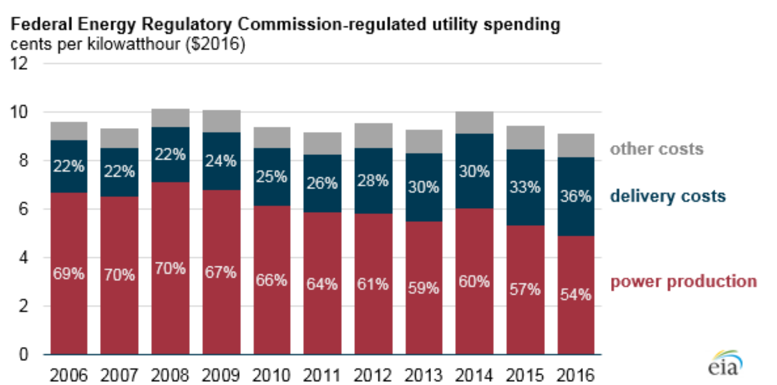


Source: PUCO, Office of the Federal Energy Advocate

Source:
Data: USDOE-EIA; PUCO, Office of the Federal Energy Advocate
Forecast: PUCO, Office of the Federal Energy Advocate.

SEPTEMBER 7, 2017

Electricity prices reflect rising delivery costs, declining power production costs



Source: U.S. Energy Information Administration, Federal Energy Regulatory Commission (FERC) Financial Reports, as accessed by Ventyx Velocity Suite

https://www.eia.gov/todayinenergy/detail.php?id=32812

LED Market Growing

lightED the ELECTRICAL DISTRIBUTOR

EXCLUSIVE FEATURES LATEST NEWS

LATEST NEWS

LED Lighting Market to Grow to $70 Billion

July 10, 2018

NEW YORK, July 09, 2018 (GLOBE NEWSWIRE) — According to the market research report published by P&S Market Research, the global LED lighting market size is projected to cross $70.2 billion by 2023, growing at a CAGR of 12.6% between 2017-2023. The growing adoption of energy efficient lighting solutions, across the globe is one of the primary factors attributing to the growth of worldwide LED lighting industry. The increased investment in infrastructure enhancement, along with continuous price erosion of LED lighting solutions is driving the growth of the market. Apart from this, increase in demand of LED for various applications of general lighting have also benefited the penetration of LEDs in recent years.

The adoption of LEDs is continuously increasing in the residential, commercial and industrial lighting applications. DOE 2014 study, energy savings forecast of solid-state lighting in general illumination applications is predicted that LED lighting will represent 84% of all lighting sales by 2030, resulting in an annual primary energy savings of 3.0 quadrillion British thermal units (quads). Increasing acceptance of LED lighting, across various lighting applications is one of the primary factors, which is likely to propel the growth of the LED lighting market.

$70B by 2023

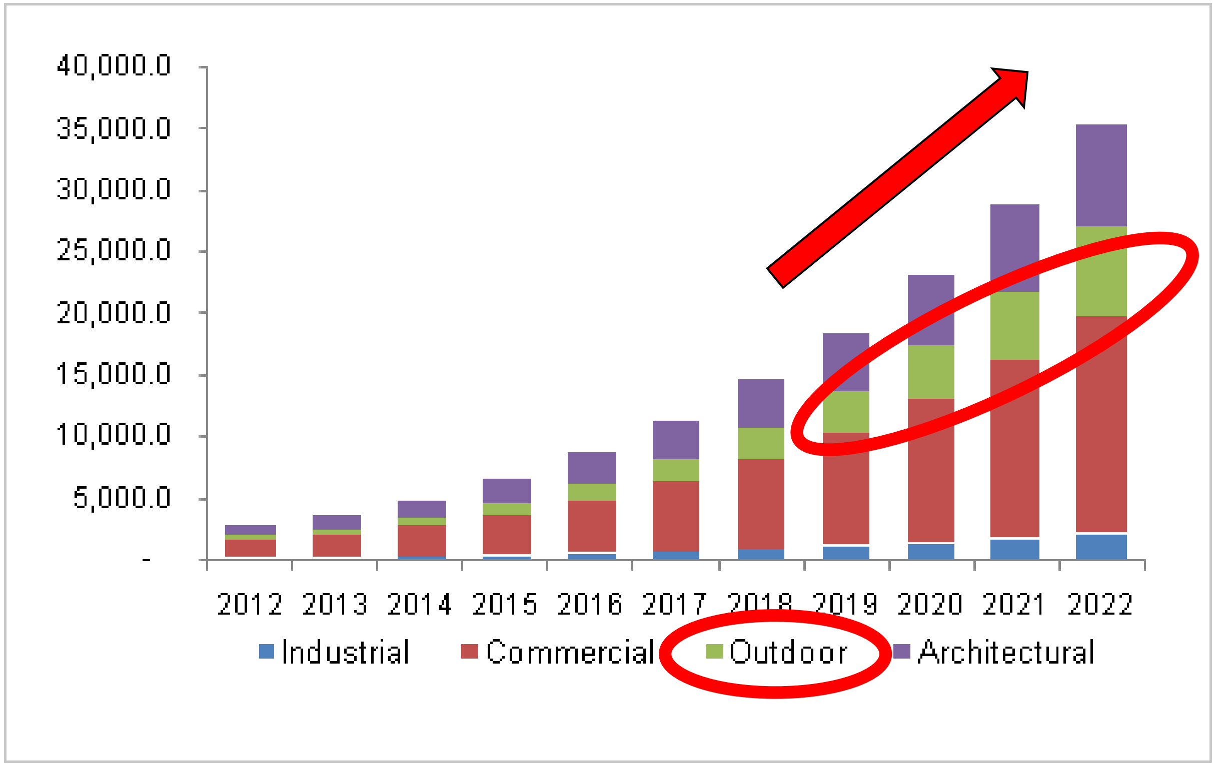
CAGR 12.6%

84% all lighting sales by 2030

LED Replacement Trends

LEDS exponential market penetration

North America industrial and commercial LED lighting market share, 2012 - 2022 (USD Million)



https://www.grandviewresearch.com/industry-analysis/industrial-commercial-led-lighting-market

LED are actually very small

http://www.qianshenglight.com/html_news/The-prices-of-LED-light-bulb-continue-to-decline-in-2017-and-2018-13.html

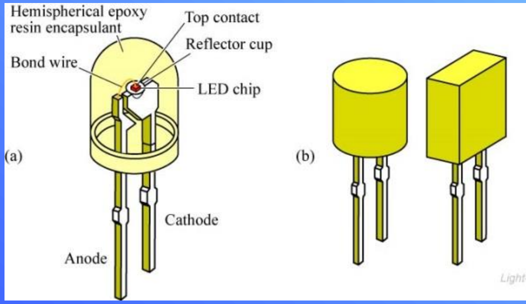


Fig. 11.1. Typical packages; (a) LED with hemispherical encapsulant; (b) LEDs with cylindrical and rectangular encapsulant.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

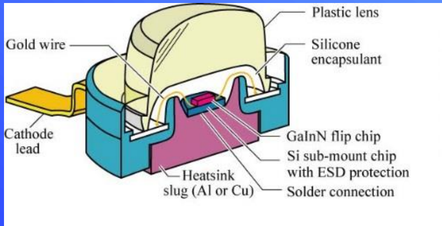


Fig. 11.2. Cross section through high-power package. The heatsink slug can be soldered to a printed circuit board for efficient heat removal. This package is called *Barracuda package* which was introduced by Lumileds Corp. (adopted from Krames, 2003).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

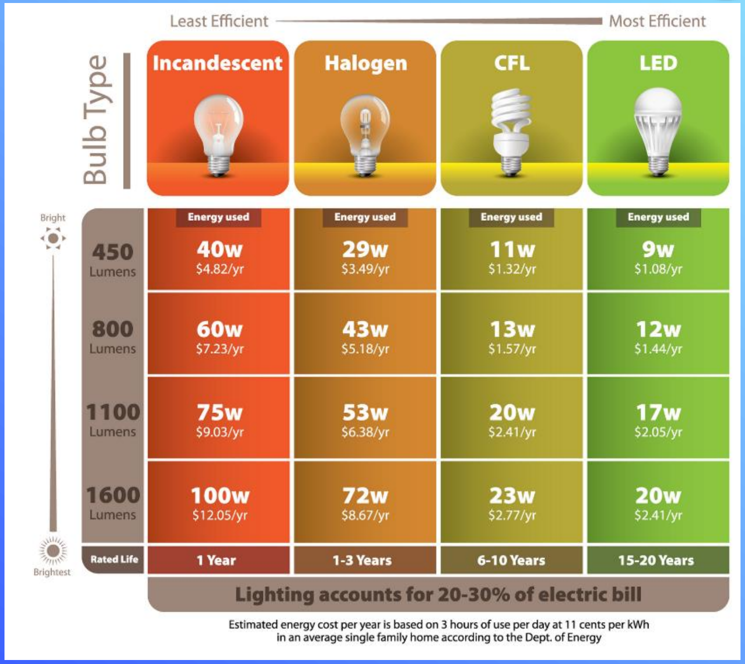
LEDS themselves are Super Small

https://www.greenbiz.com/blog/2014/01/30/5-trends-watch-commercial-lighting

E.F. Schubert, “Light Emitting Diodes”

Energy Savings w/ LEDs

THE OHIO STATE UNIVERSITY



http://emmas.me/halogen-vs-led-light-bulbs/led-savings-program-anthology-lighting-lighting-awesome-halogen-vs-led-light-bulbs-or-bulb-comparison-chart-21-compare-incandescent-halogen-fluorescent-and-led-light-bulbs/

Comparing Light Bulbs				
Bulb type	CONVENTIONAL INCANDESCENT	HALOGEN INCANDESCENT	COMPACT FLUORESCENT (CFL)	LIGHT-EMITTING DIODE (LED)
Wattage	60W	43W	15W	12W
Purchase price*	N/A	$1.25	$5.50	$14.75
Energy reduction**	N/A	-25%	-75%	-80%
Annual energy cost***	$4.80	$3.50	$1.20	$1.00
Expected service life	1,000 hrs.	1,000 - 3,000 hrs.	10,000 hrs.	25,000

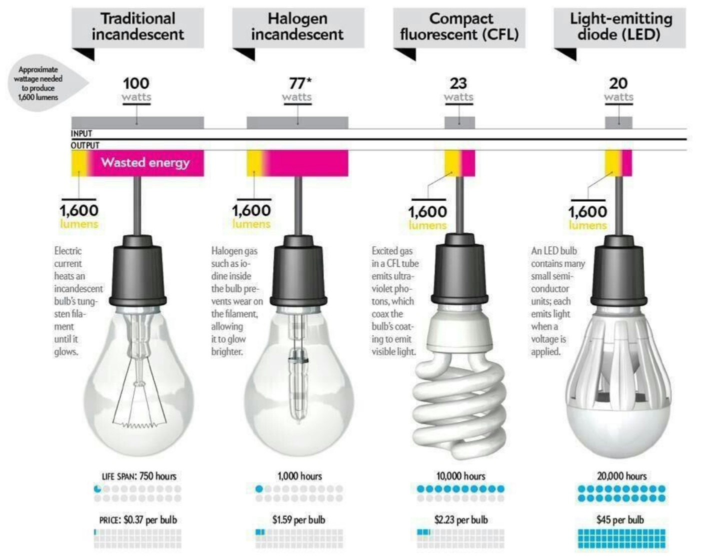
*Average price per bulb quoted on websites of big-box home-improvement centers
**Compared to 60W conventional incandescent bulb, according to energy.gov
***Based on 2 hours of use per day/electricity rate of 11 cents/kilowatt hr.

https://www.mcknights.com/marketplace/comparing-energy-efficient-light-bulbs-with-old-tech-lamps/article/627627/

LEDs vs. High-Pressure Sodium (HPS) Lamps

Fixture Type	Wattage	Lifespan		Energy Use (24 hrs/day)	Annual Cost (maintenance + electricity)
		Hrs	Yrs	Annual	@ $0.11/kWh
HPS	191 W	24,000	2.7	1,674 kWh	$195
LED	78 W	50,000	5.7	683 kWh	$75

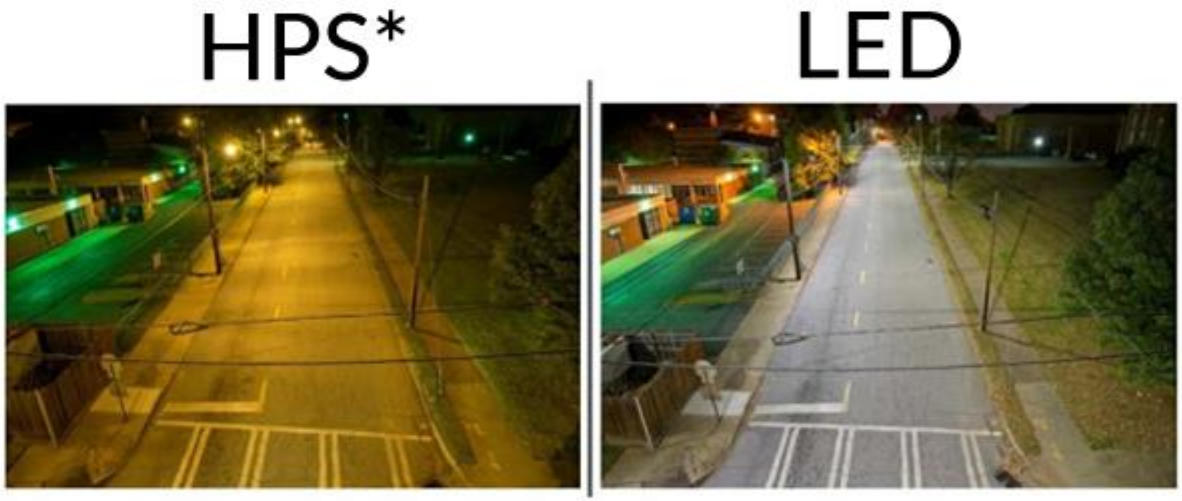
SOURCE: "Demonstration Assessment of Light-Emitting Diode (LED) Area Lights for a Commercial Garage" (U.S. Dept. of Energy, Nov. 2008)



https://www.homedit.com/the-characteristics-of-energy-efficient-light-bulbs/

https://ees2001.wordpress.com/2012/03/11/lighting-comparison-between-hps-high-pressure-sodium-and-led-equivalent/

Street Lamps



City of Atlanta – Recent roadway LED conversion

Beckwith St. near Vine St.

*HPS: High-Pressure Sodium Lighting

The movement to switch to LED lighting is sweeping the nation. Literally. From cities in California to Rhode Island, from an island off the coast of Maine to a Florida sports complex, and street lights in Minnesota to New Mexico! Why?

- Huge savings on energy costs
- Significant reduction in energy usage
- These bulbs last 4 – 5 times longer than conventional bulbs thereby reducing maintenance costs.

http://www.consumerenergysolutions.com/who-is-upgrading-to-led-lighting-now/

Environmental (Carbon)

LED Bulbs Reduced 570 Million Tons Of Carbon Emissions In 2017

BY **BRIAN SPAEN**

UPDATED 6 MONTHS AGO

LED light bulbs have seen plenty of growth in recent years with the many advantages it has over traditional lighting. Costs have come down drastically and the technology has provided more options for consumers. That's also paid off in terms of eliminating our carbon footprint, with emissions coming down by over half a billion tons in 2017.

IHS Markit, a London-based company that analyzes information and provides solutions for corporations, **released a study** that shows 570 million tons of carbon dioxide emissions were reduced thanks to the use of LED bulbs. This is an amount similar to shutting down 162 coal-fired power plants around the world. Considering LED bulbs generate just as much light, how does this all work?

Less power is needed to keep these bulbs lit up. Specifically, they use 40 percent less power than fluorescent light bulbs and double that amount for incandescent lights. Instead of looking toward wattage, a better measurement for LEDs is lumens. To achieve a bright level of 2,600 lumens, incandescent bulbs would need **150 watts** while LEDs only require between 25 to 28 watts.

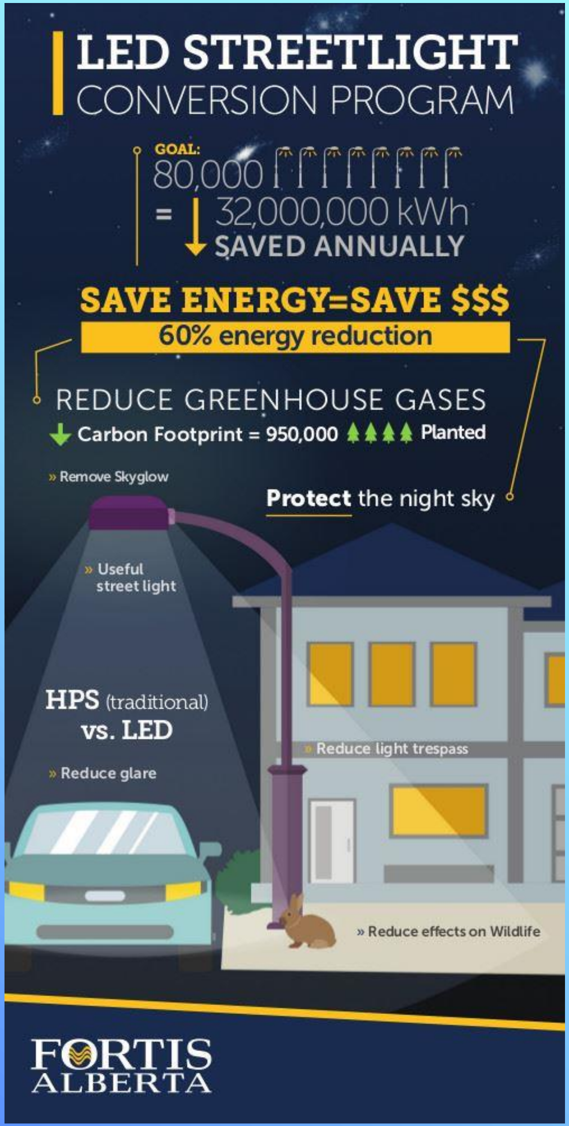
https://www.greenmatters.com/home/2018/01/02/1cHDXb/led-bulbs-carbon-emissions-2017

THE OHIO STATE UNIVERSITY

Environmental (Light Pollution)

LEDs can be focused downward, thereby "protecting the night sky"

"Why did FortisAlberta introduce an LED Conversion Streetlight Option?
FortisAlberta strives to meet the needs of its customers and in response to customer requests, the conversion option was introduced. The company is committed to improving the energy efficiency of its infrastructure, while controlling costs for our customers. We aim to be forward thinking to anticipate trends to better serve our customers."



Lighting pollution will be a major issue

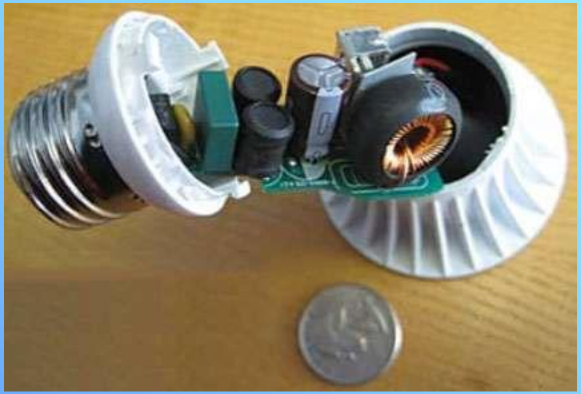
Lighting pollution has been an issue in the industry for decades, but expect clients and regulators to take it super seriously in 2018, driven by increased awareness and concerns that the low price and cooler colour temperatures of LEDs are causing more lighting pollution more than high pressure sodium ever did.

Some assert otherwise

http://luxreview.com/article/2017/12/10-big-lighting-trends-for-2018

AC versus DC

Today our electricity is still predominantly powered by alternating current, but computers, LEDs, solar cells and electric vehicles all run on DC power. And methods are now available for converting direct current to higher and lower voltages. Since direct current is more stable, companies are finding ways of using high voltage direct current (HVDC) to transport electricity long distances with less electricity loss. https://www.energy.gov/articles/war-currents-ac-vs-dc-power



The actual LEDs are very small part of bulb. AC-to-DC power electronics dominate.

https://www.energy.gov/articles/war-currents-ac-vs-dc-power

Wasted cost on AC-to-DC conversion. Larger solid waste disposal issues.

Marriage of LEDs with Solar Cells

3. Solar-powered streetlights expand off-grid solutions

While it's probably difficult to justify taking existing streetlights off the grid by using solar power or other renewable sources, it makes all sorts of sense to consider this option for new apartment buildings, roadways and buildings. Manufacturers including Clear Blue and Sol Lighting are stepping up to oblige.

So far, Sol Lighting has deployed more than 60,000 systems in more than 60 countries — that's roughly 10 megawatts of capacity. One example comes from Richmond, Va., where the city saved more than $600,000 in installation costs for more than 20 commercial grid-tied lights in a housing development project. (That's about half of what it would have cost to lay the wiring for grid-tied alternatives.) The systems have an estimated lifespan of 30 years, and have back-up batteries that can keep them running for up to five nights without being recharged by the sun.

"As much as we are a solar lighting business, we are also a wireless company and this is what people see first," said Dibs Tailor, president and CEO of Sol Lighting.

While no one really has sized the solar outdoor lighting market, the overall commercial outdoor lighting market is estimated at $11 billion. "By carefully integrating cutting-edge photovoltaic, LED and battery storage technologies into high-quality outdoor lighting products, we have made solar lighting very cost-effective and even more reliable," Tailor said.

https://www.greenbiz.com/blog/2014/01/30/5-trends-watch-commercial-lighting

First Solar (Toledo-based PV)

First Solar to provide 19MW in PV modules for two projects in Netherlands

https://www.pv-tech.org/news/first-solar-to-provide-19mw-in-pv-modules-for-two-projects-in-netherlands

Final Message

Printed from
THE TIMES OF INDIA

Dim-lit city streets cast shadow on road safety

TNN | Aug 28, 2018, 12.54 PM IST

TRICHY: Though most of the arterial roads in Trichy have been adequately lit by the urban local body (ULB), many road users are apprehensive of the quality and luminance of the LED lights in use. Citing safety of road users, particularly the pedestrians, a demand to enhance the luminance and efficacy of street lights in arterial and residential roads was placed by residents before the Trichy City Corporation (TCC).

With around 36,800 street lights spread across the 65 wards of the civic body, Trichy Corporation in early 2014 took up an energy conservation project by converting fluorescent tube lights (FTL) to LED lamps. While the conversion is under way, several complaints have been raised by the residents about the quality and luminance of street lights in arterial roads. Street lights need to be erected on the median strips on wider and spacious roads, but the authorities, including the civic body and highways department, have installed them only along the road sides resulting in poor visibility on the other end. This is evident in major roads including Rockins Road, VOC Road, McDonalds Road and Royals Road. “Street lights on city roads don’t have the required luminance. The civic body should take steps to improve the street light mechanism at present through proper and periodic maintenance,” G Kanagarajan, member, Trichy Intra-City Development Endeavours (TIDES) told TOI.

Even as the civic body claims that they are committed to converting sodium vapour lamps to LED lamps of equal efficacy, the arterial roads are still left with the comparatively power-consuming sodium vapour lamps. According to Bureau of Indian Standards (BIS), the desired lamp output in residential and commercial streets has been fixed at 6 Lux (unit of luminance) and 10 Lux respectively. However, many point out that the actual Lux level on the city roads is below the desired output.

“Conversion of old sodium vapour lamps to LED lights should be expedited. Medians strips should be set up at plausible spots to enable installation of street lights for better illumination,” N Manivannan, resident of Keelapudur, said. Trichy Corporation officials said that maintenance of street lights have been entrusted with a private firm under Public Private Partnership (PPP).

“We are monitoring the maintenance of street lights as complaints have surfaced about poor luminance. Through the Smart City programme, street lights in the entire city would be converted to LED in a year,” a senior official with Trichy Corporation said.

Even India is racing to replace streetlamps with LEDS

Don’t be left behind!

Any Questions?

Prof. Paul R. Berger, Ph.D.
IEEE Fellow; IEEE Distinguished Lecturer (EDS)

Ohio State University
Department of Electrical and Computer Engineering
Department of Physics

Mailing address: The Ohio State University
Department of Electrical and Computer Engineering
205 Dreese Laboratory
2015 Neil Avenue
Columbus, Ohio 43210-1272

Campus Address: 201 Caldwell Laboratory
Email: pberger@ieee.org
URL: http://www.ece.osu.edu/~berger/

Backup Slides

DO NOT PRINT!

Building Integrated Solar Cells

OPV Curtain

San Francisco bus stop

Solar “Curtain Wall”

German Pavilion – Milan 2015 Expo

Solar Cell Trees Power Nighttime LEDS

Belectric & Merck

Video: https://www.schmidhuber.de/sites/default/files/field/video/2.2_ecotec_1806_ta_e_sp_web_630.mp4

https://www.schmidhuber.de/en/project/german-pavilion-expo-milano-2015-0

Building Integrated Solar Cells

Photovoltaic window

Source: Next Energy Technologies Inc

Solar Window

https://nextenergy.tech/

Human Eye Response

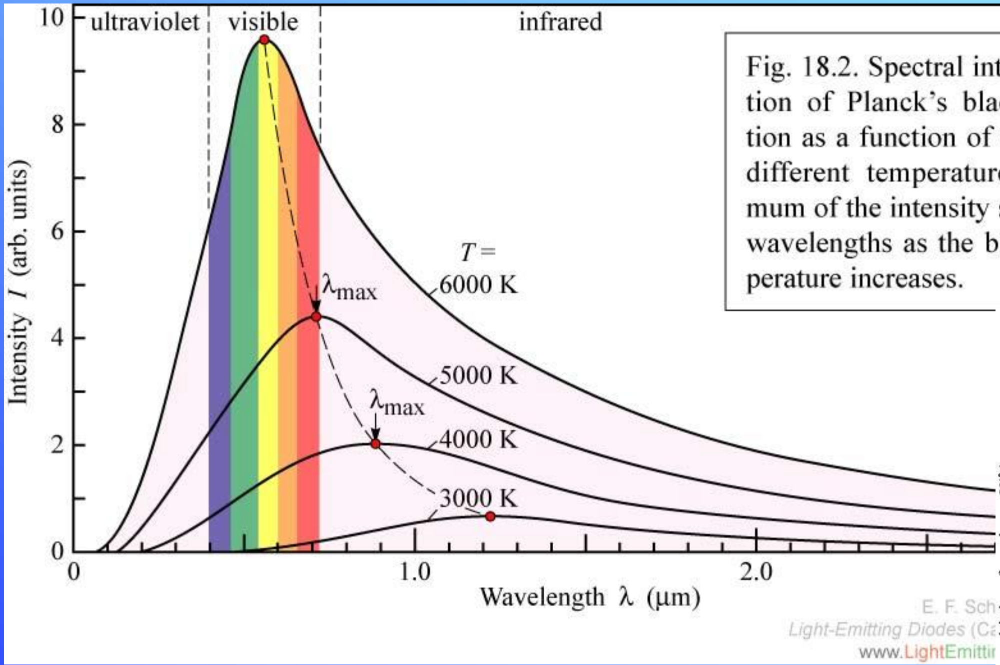


Fig. 18.2. Spectral intensity distribution of Planck's black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.

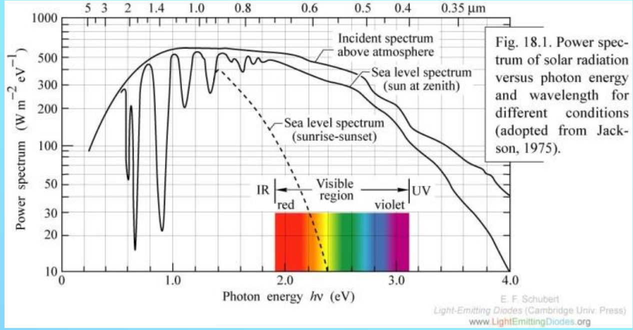


Fig. 18.1. Power spectrum of solar radiation versus photon energy and wavelength for different conditions (adopted from Jackson, 1975).

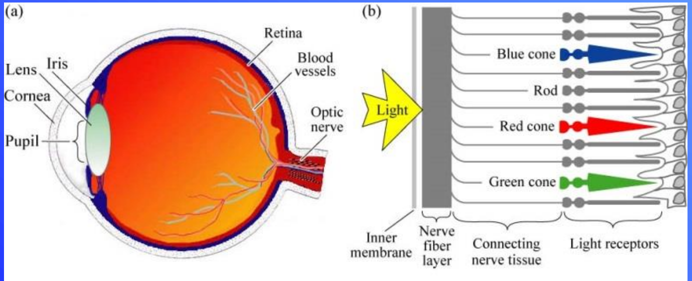


Fig. 16.1. (a) Cross section through a human eye. (b) Schematic view of the retina including rod and cone light receptors (adapted from Encyclopedia Britannica, 1994).

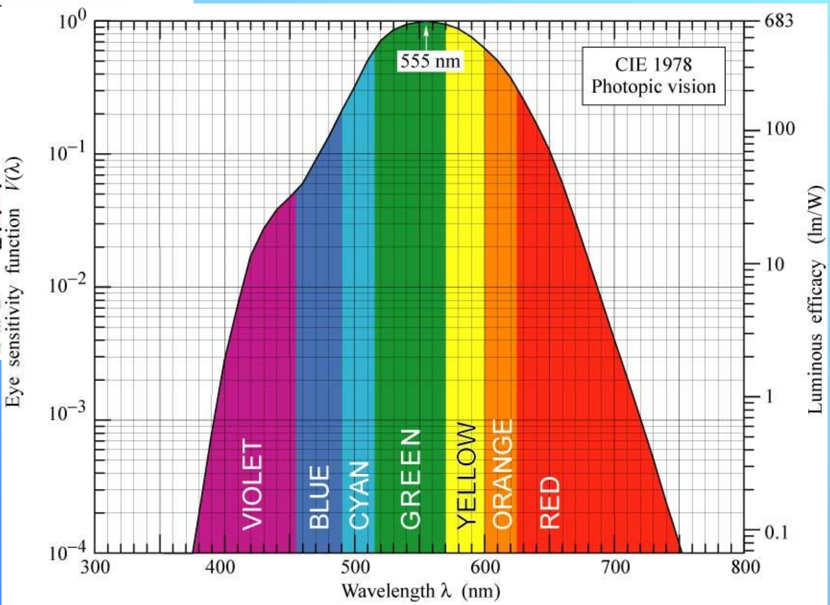


Fig. 16.7. Eye sensitivity function, $V(\lambda)$, (left ordinate) and luminous efficacy, measured in lumens per Watt of optical power (right ordinate). $V(\lambda)$ is greatest at 555 nm. Also given is a polynomial approximation for $V(\lambda)$ (after 1978 CIE data).

Photometric Definitions

Photopic vision – human vision at high ambient light levels (**daylight**), primarily mediated by cones (color) near center of retina when pupil is **not** dilated

Scotopic vision – human vision at low ambient light levels (**night**) primarily mediated by rods (black/white) near periphery of retina when pupil is dilated.

Luminous Intensity – represents the **light intensity** perceived by the human eye from a light source. International System of Units (SI unit) is the **candela (cd)** – a monochromatic light source emitting an optical power of (1/683) Watt at 555 nm into a solid angle of 1 steradian (sr) has a luminous intensity of 1 candela (based upon one standardized candle, i.e. a plumber's candle).

Luminous Flux – represents the **light power** perceived by the human eye from a light source. International System of Units (SI unit) is the **lumen (lm)** – a monochromatic light source emitting an optical power of (1/683) Watt at 555 nm has a luminous flux of 1 lumen.

1 candela = **1 cd** = 1 lumen per steradian = **1 cd/sr**

Isotropically emitting light source of luminous intensity of **1 cd** has a
→ luminous flux of **4π lm** = **12.57 lm**

Photometric Definitions

Eye sensitivity function V(λ) – conversion between radiometric and photometric units is provided by eye sensitivity function.

Luminance – ratio of the luminous intensity emitted in a certain direction (measured in cd) divided by the projected source in that direction (measured in cm^2).

Illuminance –luminous flux incident per unit area (measured in lux).

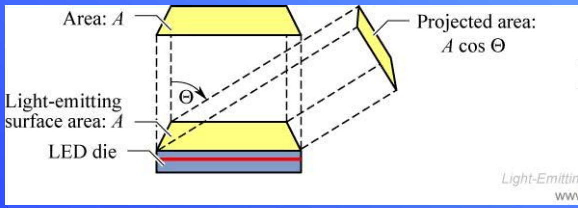


Fig. 16.5. Area of LED, A, and projected area, $A \cos \Theta$, used for the definition of the luminance of an LED.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Fig. 16.4. Plumber's candle as used by plumbers to melt lead when joining water pipes in the 19th century.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Figure-of-merit	Explanation Unit	Unit
Luminous Efficacy	Luminous flux per optical unit power	lm/W
Luminous Efficiency	Luminous flux per input electrical unit power	lm/W
Luminous intensity Efficiency	Luminous flux per sr per input electrical power	cd/W
Luminance	Luminous flux per sr per chip unit area	cd/cm^2
Power efficiency	Optical output power per unit input electrical unit power	%
Internal quantum efficiency	Photons emitted in active region per unit electron injected	%
External quantum efficiency	Photons emitted from LED per electron injected	%
Extraction efficiency	Escape probability of photons emitted in active region	%

Photometric Fun Facts

Light Source	Luminous Efficiency
Edison's first light bulb	1.4 lm/W
Tungsten filament light bulbs	15 - 20 lm/W
Quartz halogen light bulbs	20 - 25 lm/W
Fluorescent light bulbs and compact bulbs	50 - 80 lm/W
Mercury vapor light bulbs	50 - 60 lm/W
Metal halide light bulbs	80 - 125 lm/W
High-pressure sodium vapor light bulbs	100 - 140 lm/W

Color	Wavelength
Ultraviolet	< 390 nm
Violet	390 - 455 nm
Blue	455 - 490 nm
Cyan	490 - 515 nm
Green	515 - 570 nm
Yellow	570 - 600 nm
Amber	590 - 600 nm
Orange	600 - 625 nm
Red	625 - 720 nm
Infrared	> 720 nm

Illumination condition	Illuminance
Full moon	1 lux
Street lighting	10 lux
Home lighting	20 - 300 lux
Office desk lighting	100 - 1000 lux
Surgery lighting	10,000 lux
Direct lighting	100,000 lux

Chromaticity

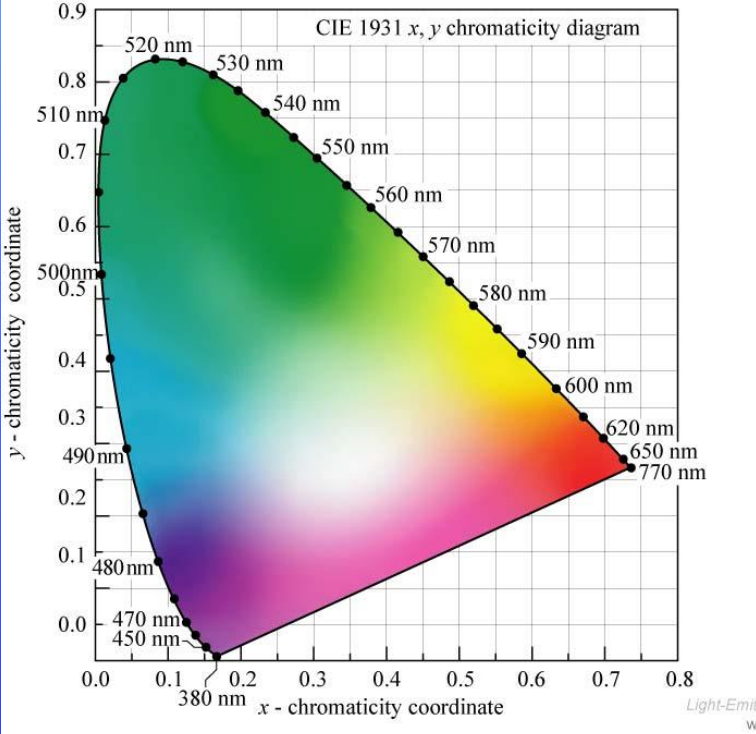


Fig. 17.2. CIE 1931 (x, y) chromaticity diagram. Monochromatic colors are located on the perimeter and white light is located in the center of the diagram.

Color Perception

The properties of color which are inherently distinguishable by the human eye are hue, saturation, and brightness. While we know that the spectral colors can be one-to-one correlated with light wavelength, the perception of light with multiple wavelengths is more complicated.

It is found that many different combinations of light wavelengths can produce the same perception of color. This can be put in perspective with the CIE chromaticity diagram.

The white at the central achromatic point can also be achieved with many different mixtures of light, e.g. with complementary colors. If you have two illuminating sources which appear to be equally white, they could be obtained by adding two distinctly different combinations of colors. This implies that if you used them to illuminate a colored object which selectively absorbs certain colors, that object might look very different when viewed with the two different "white" lights.

Source: hyperphysics.phy-astr.gsu.edu

What are the CIE coordinates of the OLED?

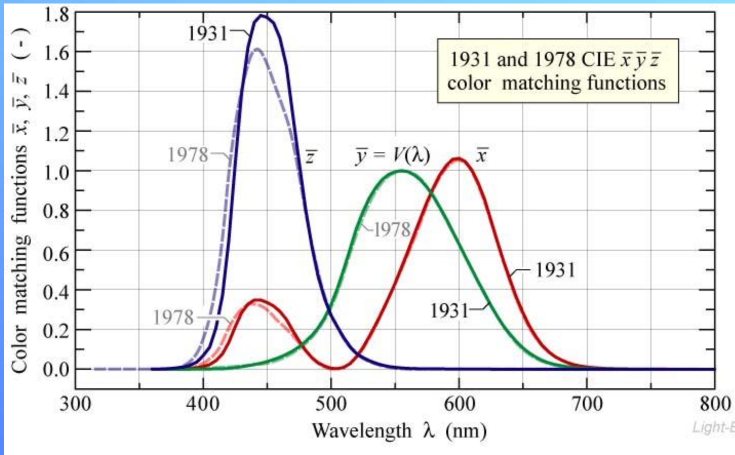


Fig. 17.1. CIE (1931) and CIE (1978) $\bar{x}\bar{y}\bar{z}$ color matching functions (CMFs). The $\bar{y}$ CMF is identical to the eye sensitivity function $V(\lambda)$. Note that the CIE 1931 CMF is the currently valid official standard.

- Use the X, Y, Z photopic response curves (above).
- Multiply the OLED spectrum with each of the X, Y, and Z curves
- Add all the values in each column to obtain three numbers x, y, z, respectively.
- The (x , y) CIE coordinates are then given by x = x / (x+y+z), y = y / (x+y+z). Plot the (x , y) coordinates on the CIE plot contained in CIE chromaticity diagram.pdf.

Color Purity

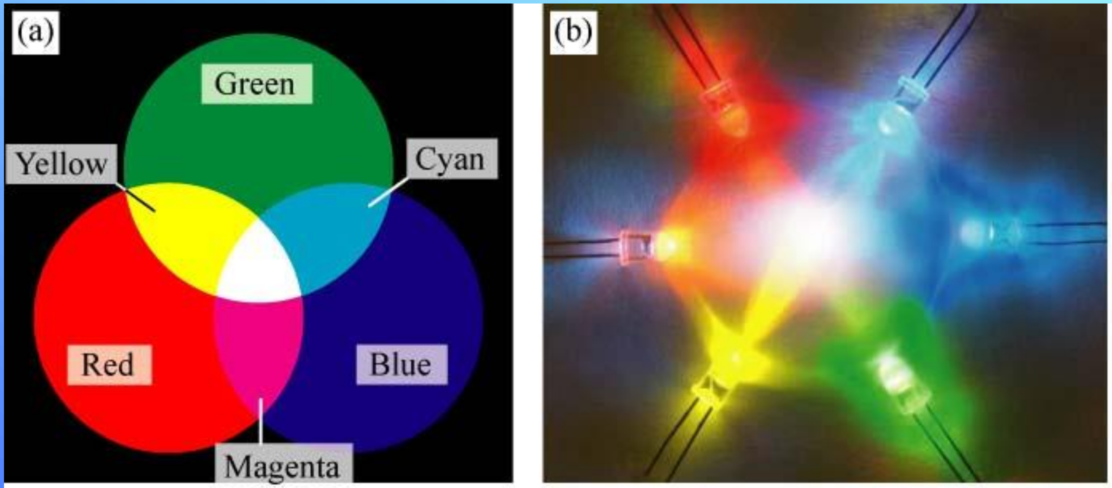


Fig. 19.1. (a) Schematic of additive color mixing of three primary colors. (b) Additive color mixing using LEDs.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

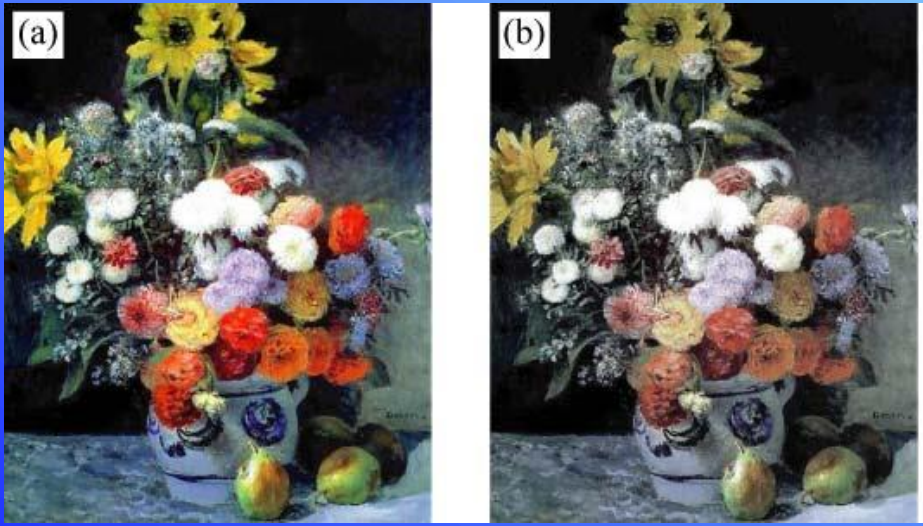


Fig. 19.3. Artwork entitled "Fleurs dans un vase" illuminatd with (a) high-CRI source and (b) low-CRI source (Auguste Renoir, French impressionist, 1841–1919) .

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Downconversion via Phosphor

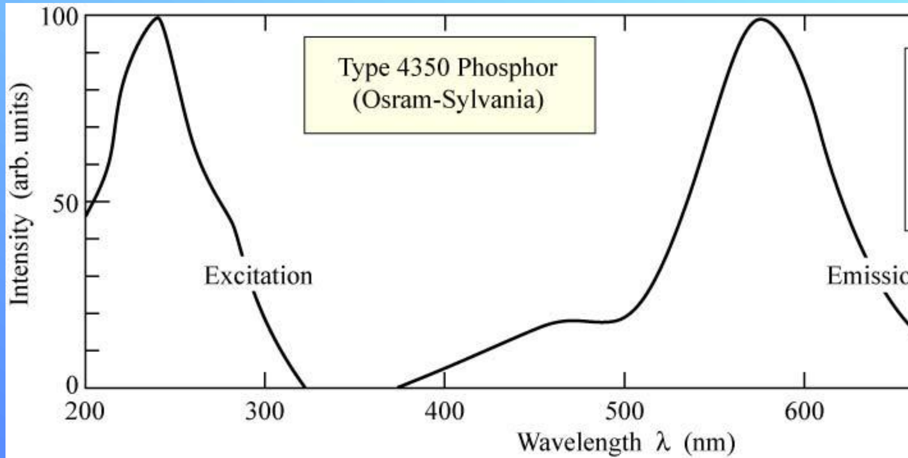


Fig. 21.2. Absorption and emission spectrum of a commercial phosphor (after Osram-Sylvania, 2000).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

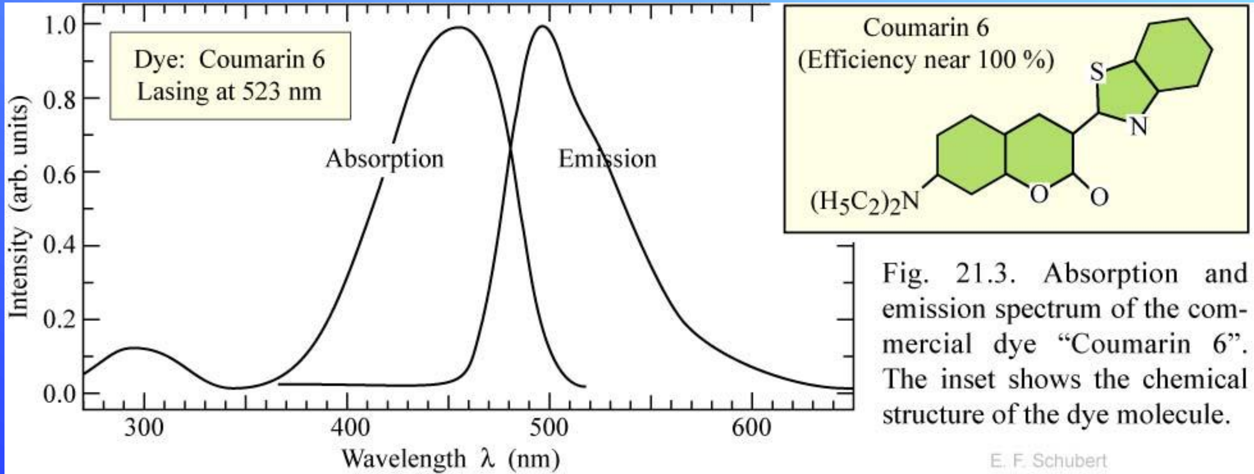


Fig. 21.3. Absorption and emission spectrum of the commercial dye "Coumarin 6". The inset shows the chemical structure of the dye molecule.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Downconversion via Phosphor II

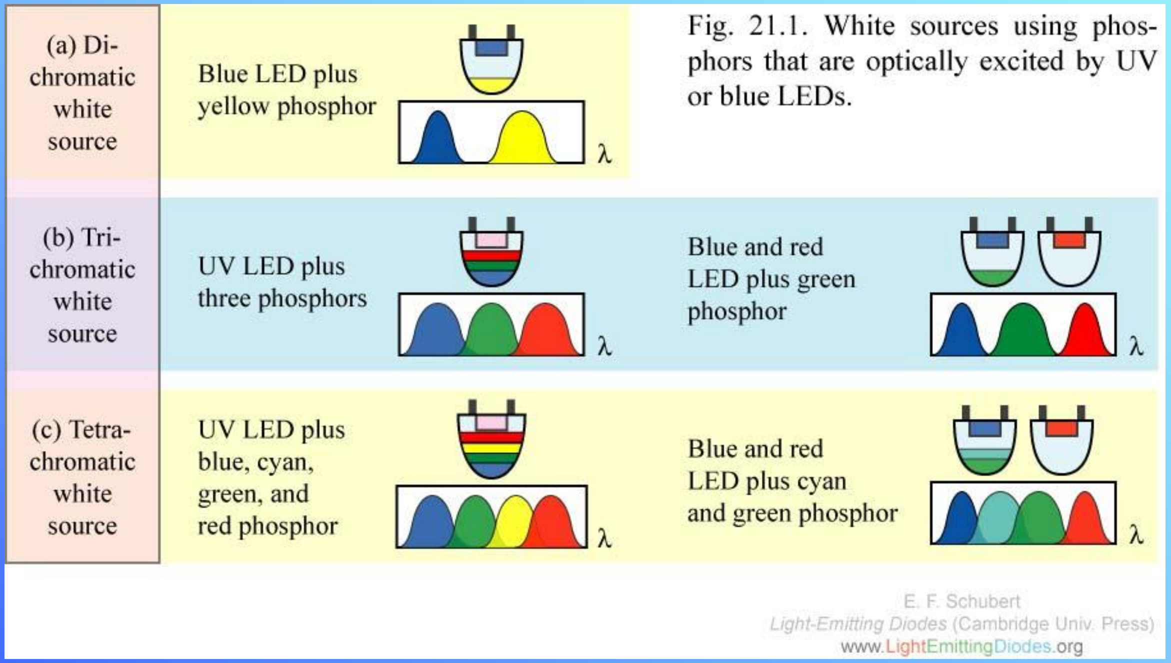


Fig. 21.1. White sources using phosphors that are optically excited by UV or blue LEDs.

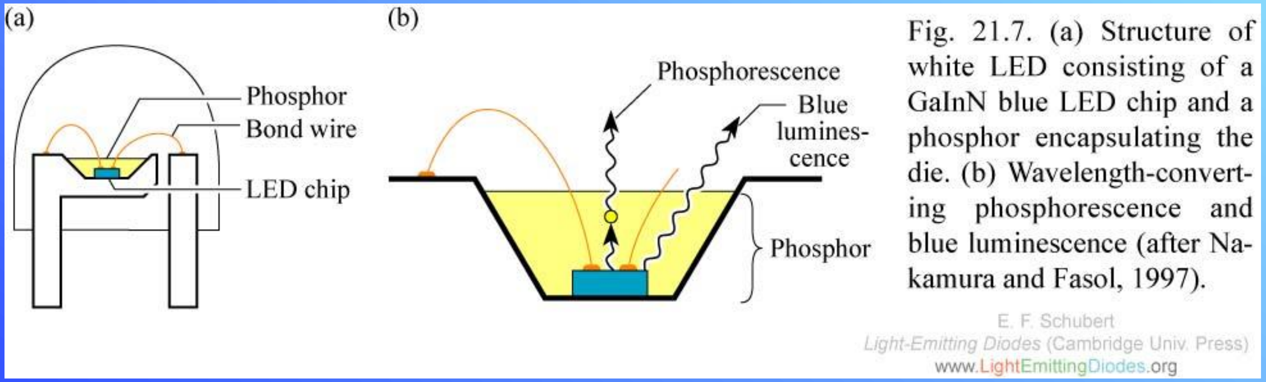


Fig. 21.7. (a) Structure of white LED consisting of a GaInN blue LED chip and a phosphor encapsulating the die. (b) Wavelength-converting phosphorescence and blue luminescence (after Nakamura and Fasol, 1997).

Basic Operation

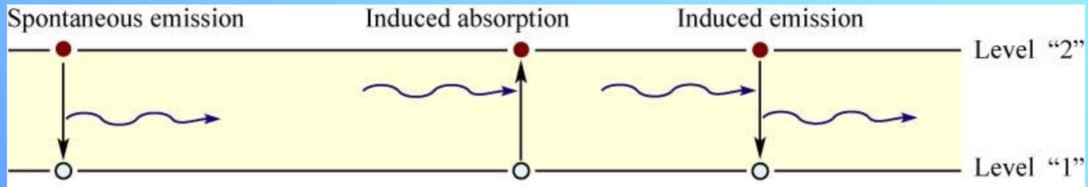


Fig. 3.5. Spontaneous emission, induced absorption, and induced emission events in the two-level atom model.

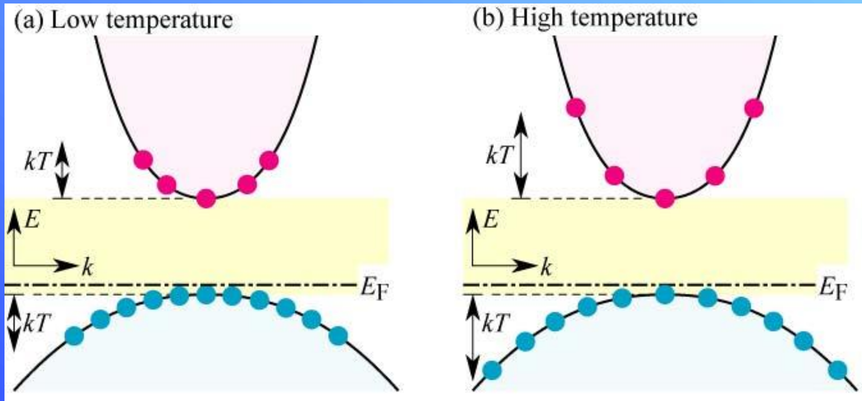


Fig. 3.2. Carrier distribution at (a) low and (b) high temperatures. Recombination probability decreases at high temperatures due to reduced number of carriers per d*k* interval.

Basic LED Operation

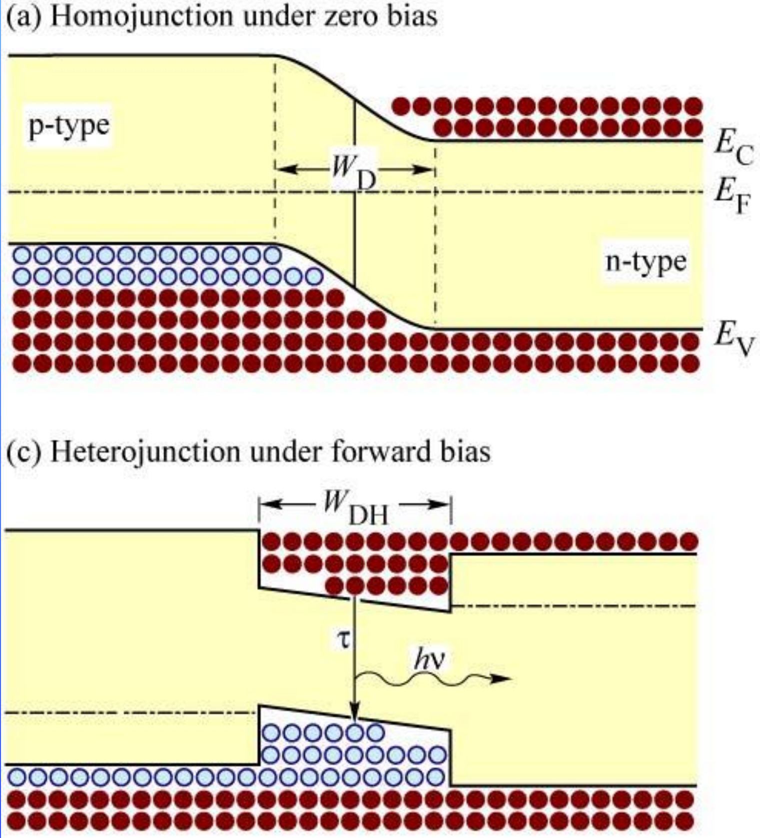


Fig. 4.6. P-n homojunction under (a) zero and (b) forward bias. (c) P-n heterojunction under forward bias. In homojunctions, carriers diffuse, on average, over the diffusion lengths L_n and L_p before recombining. In heterojunctions, carriers are confined by the heterojunction barriers.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Color Tuning via Bandgap

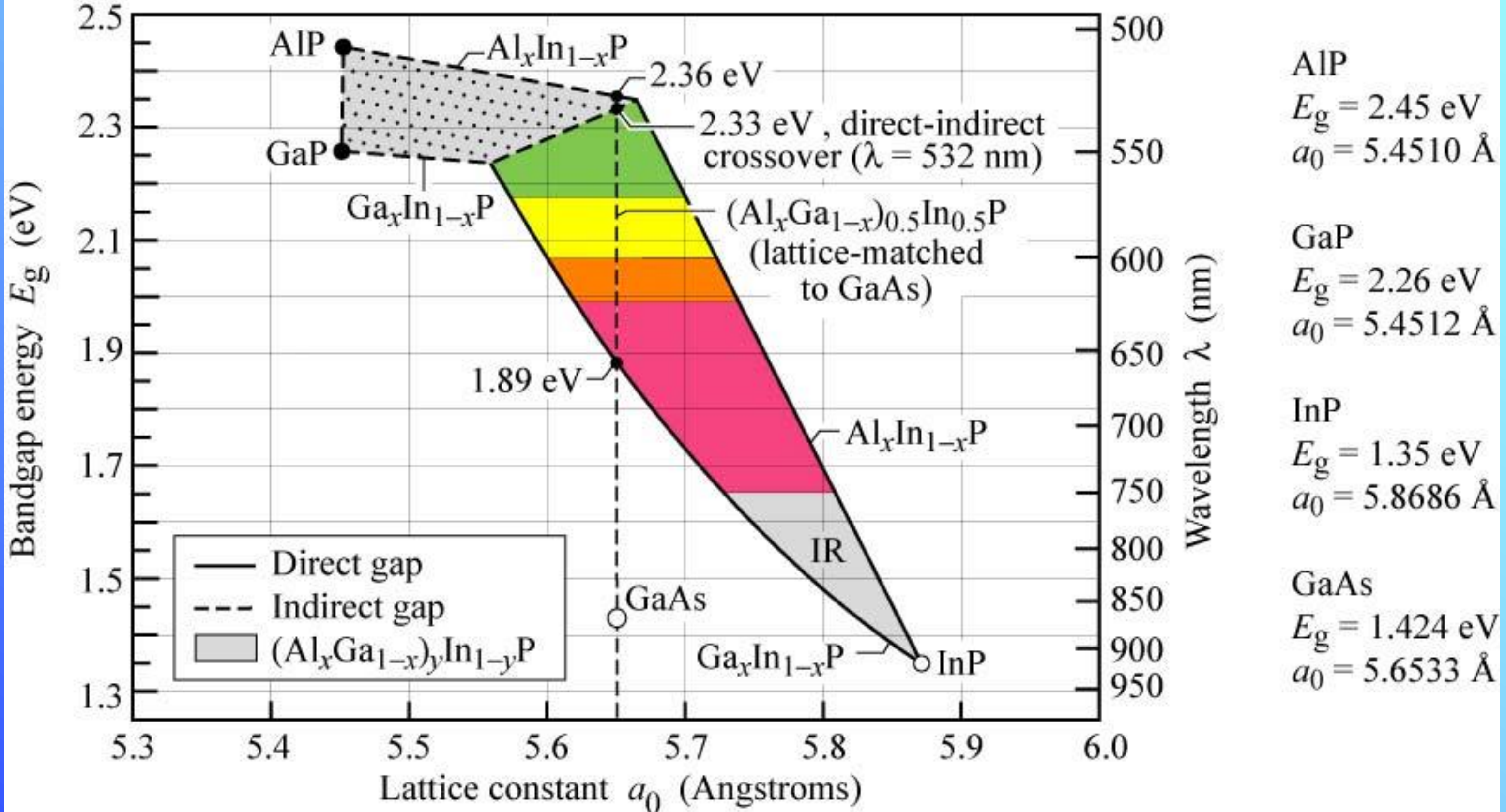


Fig. 12.9. Bandgap energy and corresponding wavelength versus lattice constant of $(Al_xGa_{1-x})_yIn_{1-y}P$ at 300 K. The dashed vertical line shows $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ lattice matched to GaAs (adopted from Chen *et al*., 1997).

THE OHIO STATE UNIVERSITY

Influence of Bandgap on I-V

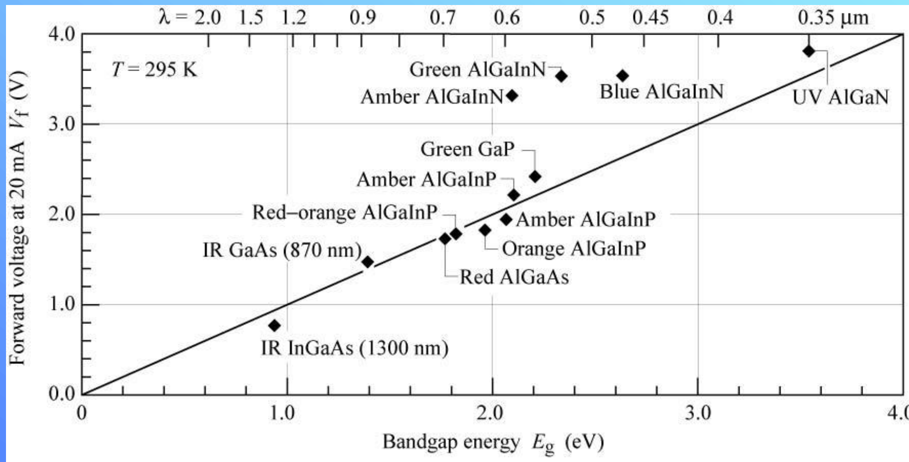


Fig. 4.3. iode forward voltage versus bandgap energy for LEDs made from different materials (after Krames *et al.*, 2000; updated with UV LED data of Emerson *et al.*, 2002).

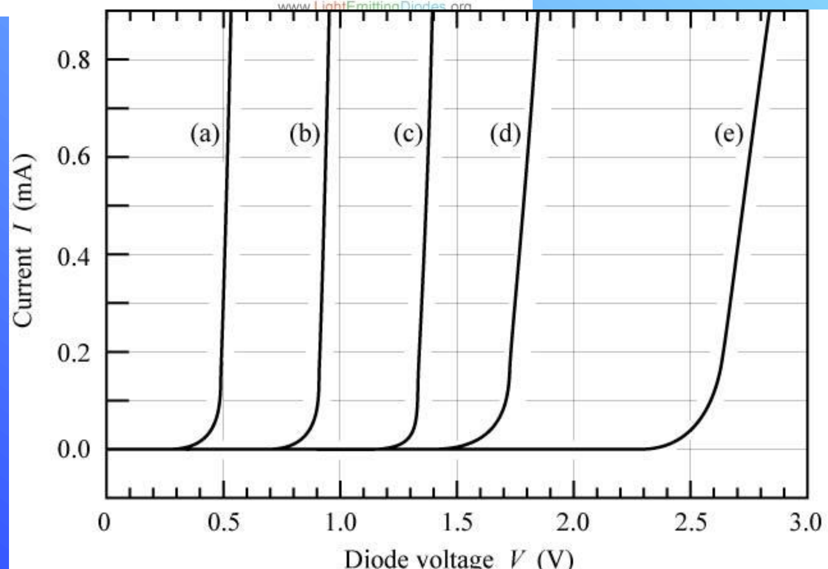


Fig. 4.2. Room-temperature current–voltage characteristics of p-n junctions made from different semiconductors.

Quantum Wells

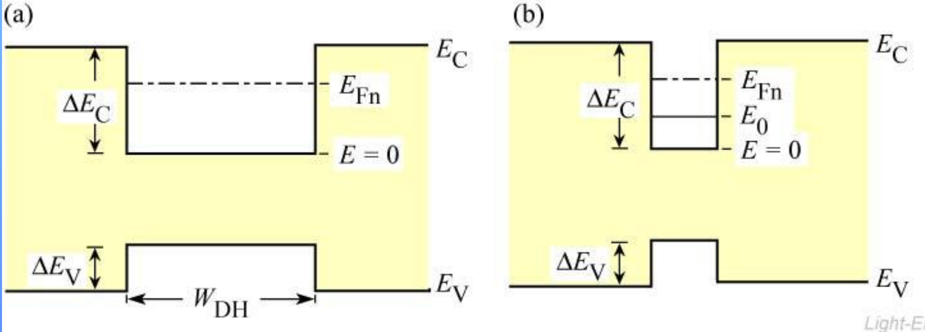


Fig. 4.10. Fermi level (E_{Fn}) and subband level (E_0) in (a) a double heterostructure and (b) a quantum well structure.

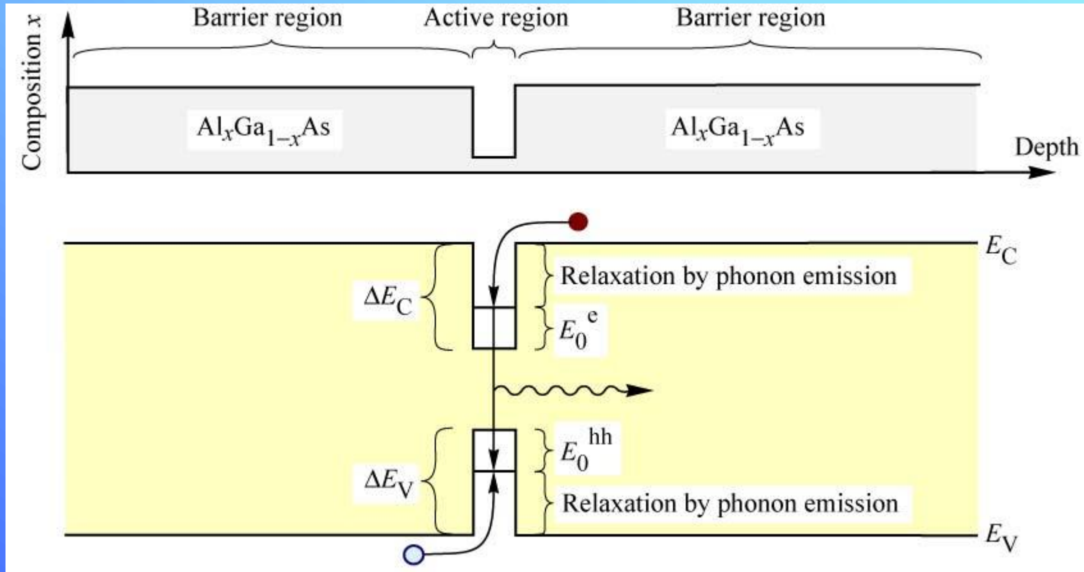


Fig. 4.13. (a) Chemical composition and (b) band diagram of a quantum well structure, illustrating the energy loss of carriers as they are captured into the quantum well.

Linewidth

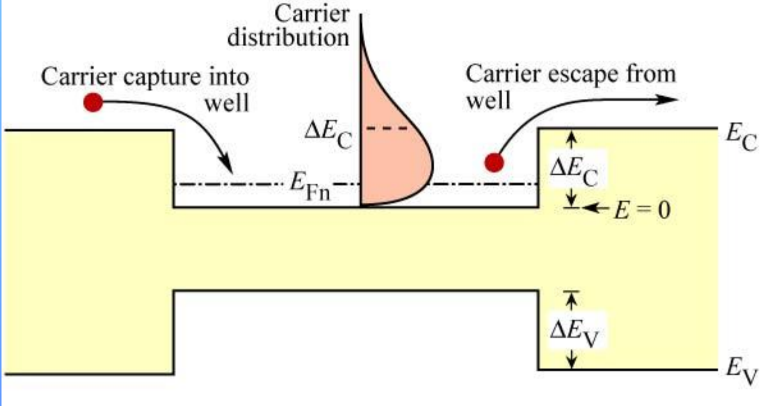


Fig. 4.9. Carrier capture and escape in a double heterostructure. Also shown is the carrier distribution in the active layer.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Maximum intensity occurs at: E = Eg + ½ kT

Linewidth: ΔE = 1.8 kT

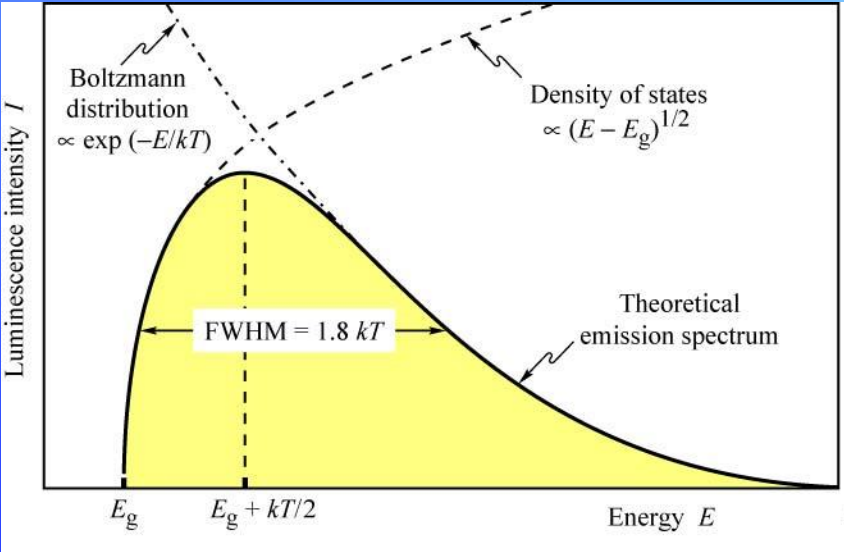


Fig. 5.2. Theoretical emission spectrum of an LED. The full width at half maximum (FWHM) of the emission line is 1.8 kT.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Non-Ideal Operation

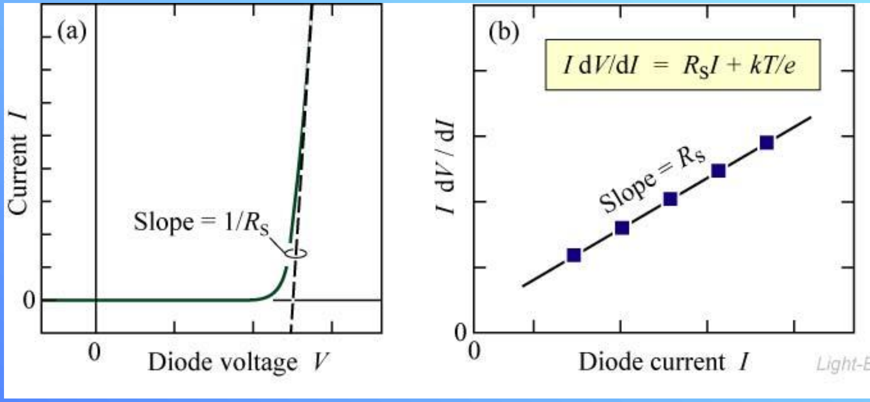
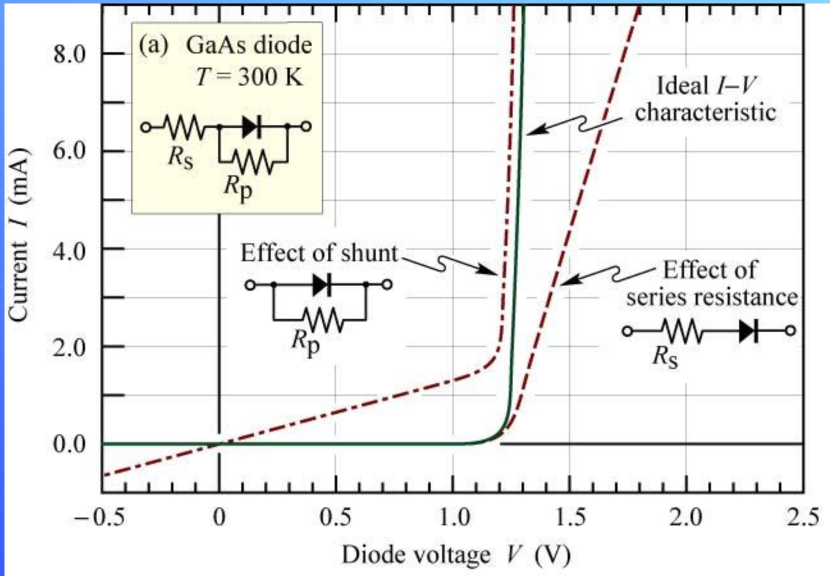


Fig. 4.5. Methods for evaluating diode series resistance. (a) Tangent for $V > V_{th}$ provides R_S. (b) Equation shown as inset is valid for forward bias ($V >> kT/e$).



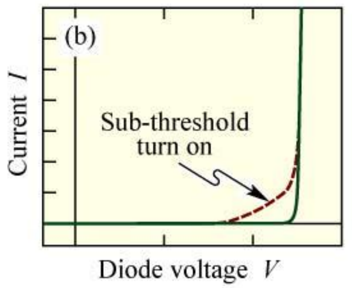


Fig. 4.4. (a) Effect of series and parallel resistance (shunt) on I–V characteristic. (b) I–V with with clearly discernable sub-threshold turn-on caused by defects or surface states.

Lambertian Emission

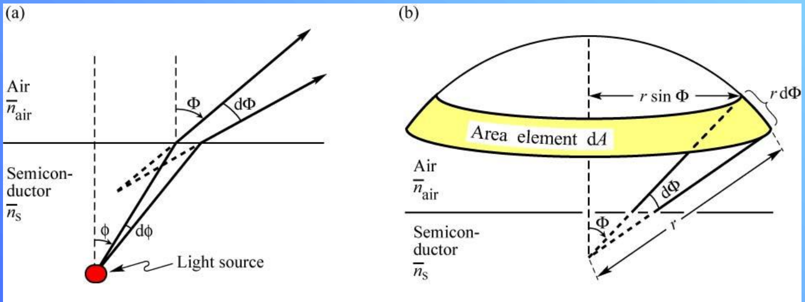


Fig. 5.4. Geometrical model used to derive the Lambertian emission pattern. (a) The light emitted into angle dϕ inside the semiconductor is emitted into the angle dΦ in air. (b)Illustration of the area element dA of the calotte-shaped section of the sphere.

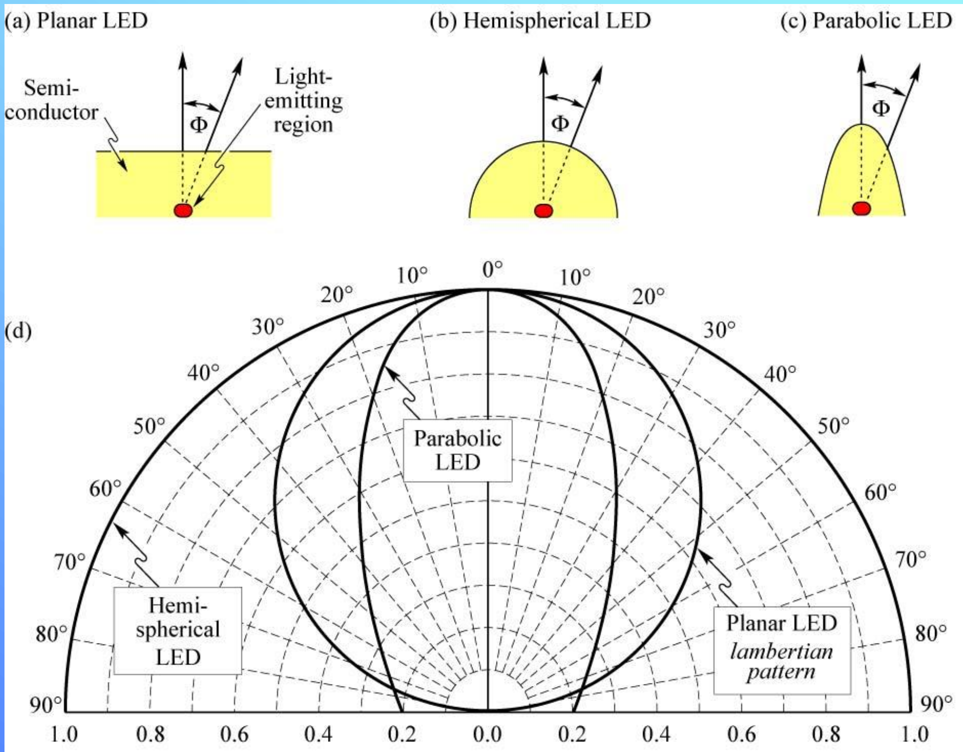


Fig. 5.5. Light-emitting diodes with (a) planar, (b) hemispherical, and (c) parabolic surfaces. (d) Far-field patterns of the different types of LEDs. At an angle of Φ = 60°, the lambertian emission pattern decreases to 50 % of its maximum value occurring at Φ = 0°. The three emission patterns are normalized to unity intensity at Φ = 0°.

Shaping LEDs

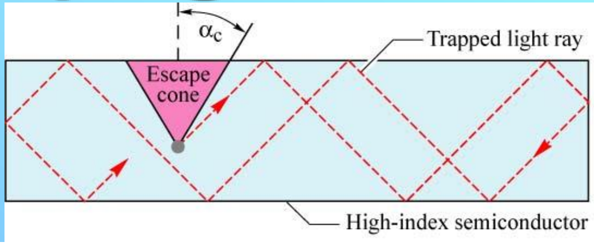


Fig. 9.3. "Trapped light" in a rectangular-parallelepiped-shaped semiconductor unable to escape for emission angles greater than α_c due to total internal reflection.

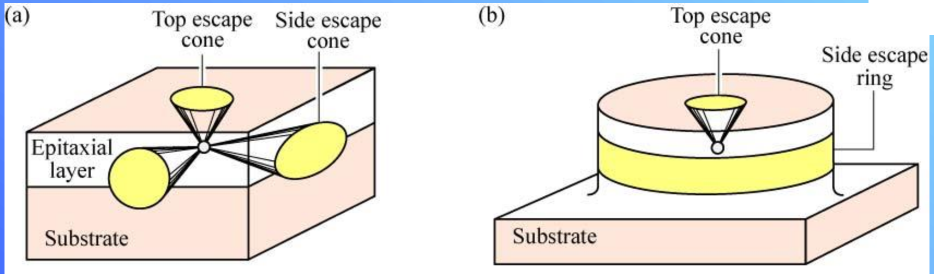


Fig. 9.5. Illustration of different geometric shapes of LEDs. (a) Rectangular parallelepipedal LED die with a total of six escape cones. (b) Cylindrical LED die with a top escape cone and a side escape ring.

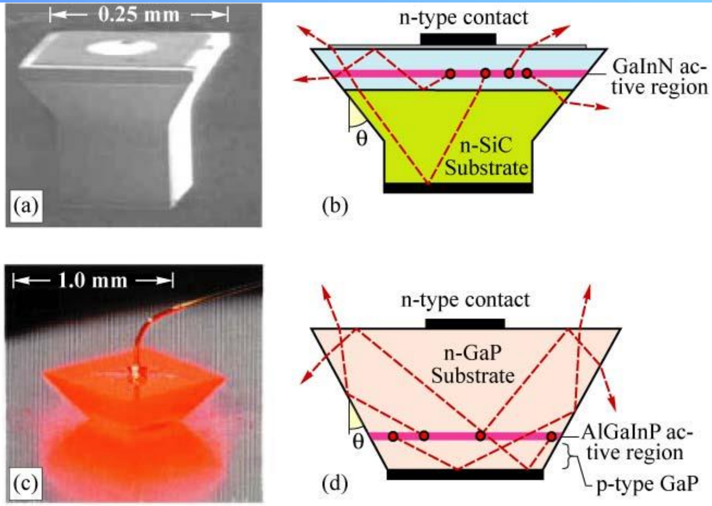


Fig. 9.6. Die-shaped devices: (a) Blue GaInN emitter on SiC substrate with trade name "Aton". (b) Schematic ray traces illustrating enhanced light extraction. (c) Micrograph of truncated inverted pyramid (TIP) AlGaInP/GaP LED. (d) Schematic diagram illustrating enhanced extraction (after Osram, 2001; Krames *et al.*, 1999).

Texturing LEDs

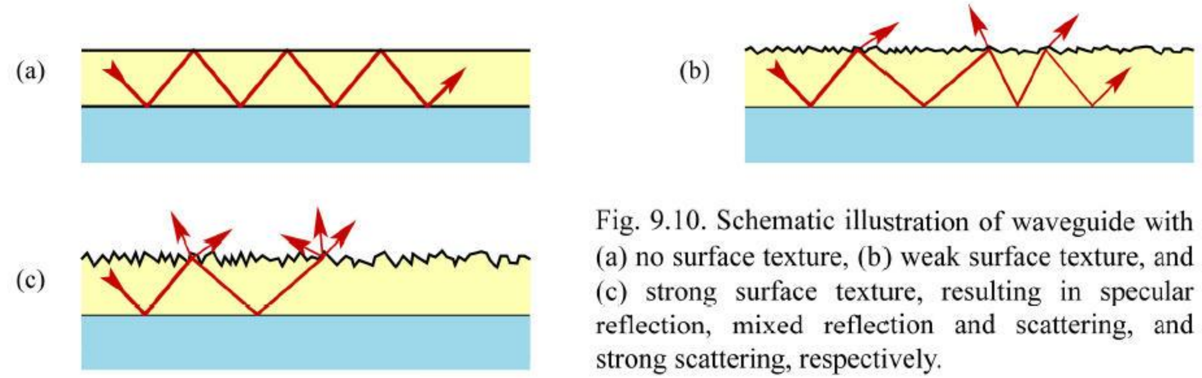


Fig. 9.10. Schematic illustration of waveguide with (a) no surface texture, (b) weak surface texture, and (c) strong surface texture, resulting in specular reflection, mixed reflection and scattering, and strong scattering, respectively.

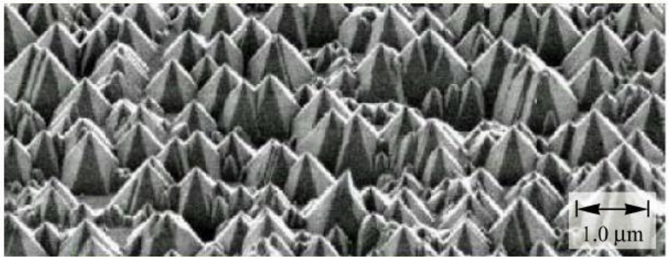


Fig. 9.8. Scanning electron micrograph of strongly textured GaN surface (after Haerle, 2004).

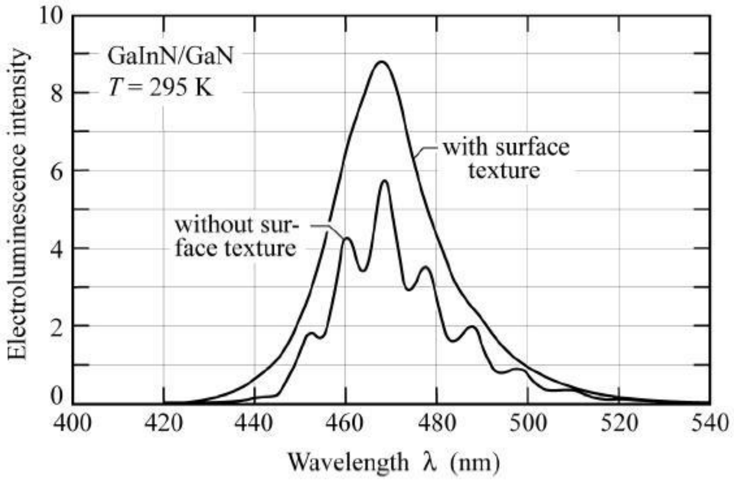


Fig. 9.9. Emission spectrum of GaInN blue LED with and without surface texture. The spectrum exhibits Fabry-Perot interference fringes for the device with a smooth surface (after Haerle, 2004).

Current Spreading/Transparent Subs

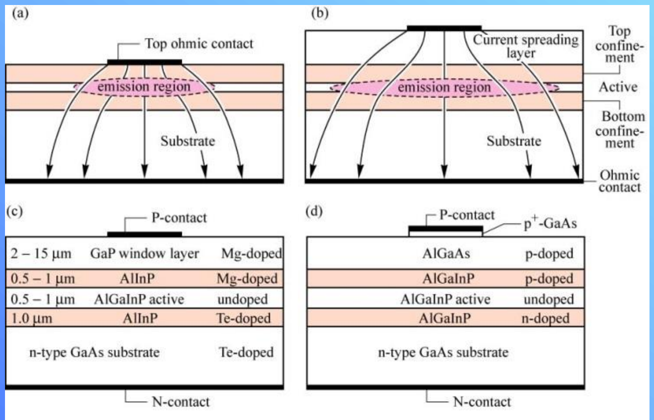


Fig. 8.2. Current-spreading structures in high-brightness AlGaInP LEDs. Illustration of the effect of a current-spreading layer for LEDs (a) without and (b) with a spreading layer on the light extraction efficiency. (c) GaP current-spreading structure (Fletcher *et al.*, 1991a, 1991b). (d) AlGaAs currect-spreading structure (Sugawara *et al.*, 1992a, 1992b).

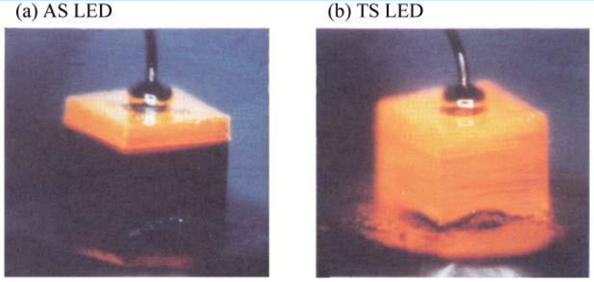


Fig. 9.11. (a) Amber AlGaInP LED with a GaP window layer and absorbing GaAs substrate (AS). (b) Amber AlGaInP LED with a GaP window layer and a transparent GaP substrate (TS) fabricated by wafer bonding. Conductive Ag-loaded die-attach epoxy can be seen at bottom (after Kish and Fletcher, 1997).

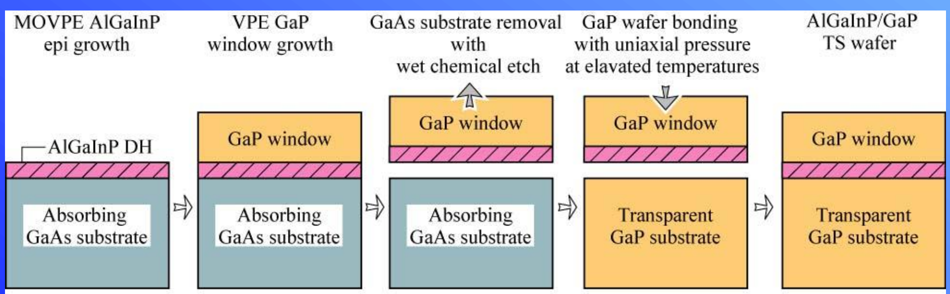


Fig. 9.9. Schematic fabrication process for wafer-bonded transparent substrate (TS) AlGaInP/GaP LEDs. After the selective removal of the original GaAs substrate, elevated temperature and uniaxial pressure are applied, resulting in the formation of a single TS LED wafer (adopted from Kish *et al.*, 1994).

Transparent Substrate (TS) is 1.5-3.0× higher external efficiency

Reflectors

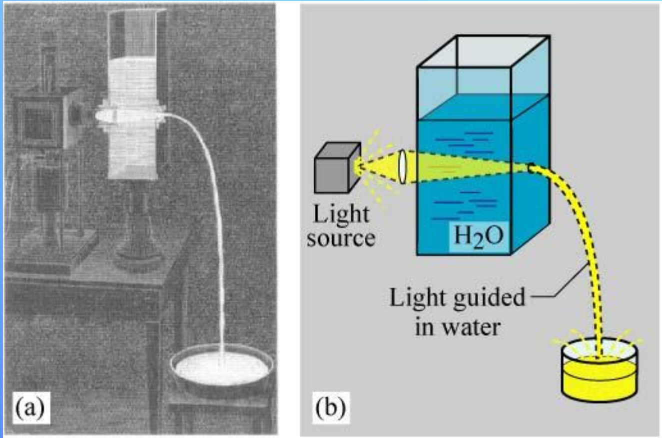


Fig. 10.5. (a) Historical drawing and (b) schematic illustration of apparatus used in 1841 by Swiss engineer Daniel Colladon to demonstrate the guiding of light by total internal reflection in a jet of water.

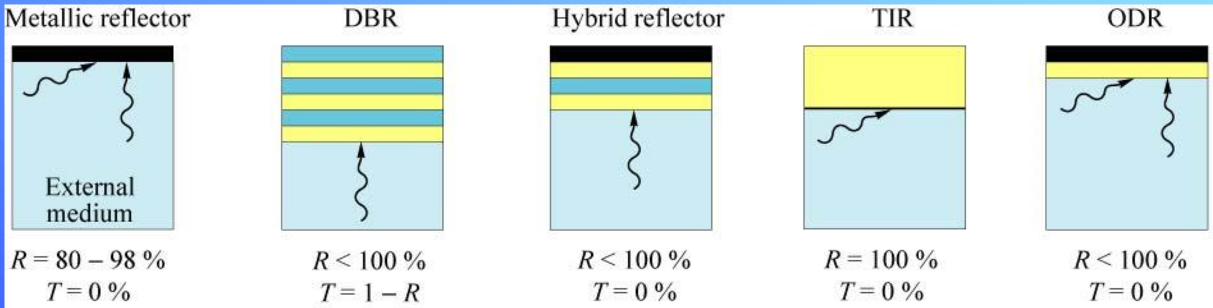


Fig. 10.1. Different types of reflectors including metallic reflector, distributed Bragg reflector (DBR), hybrid reflector, total internal reflector (TIR), and omni-directional reflector (ODR). Also given are angles of incidence for high reflectivity and typical reflectances and transmittances.

THE OHIO STATE UNIVERSITY

Distributed Bragg Reflectors (DBR)

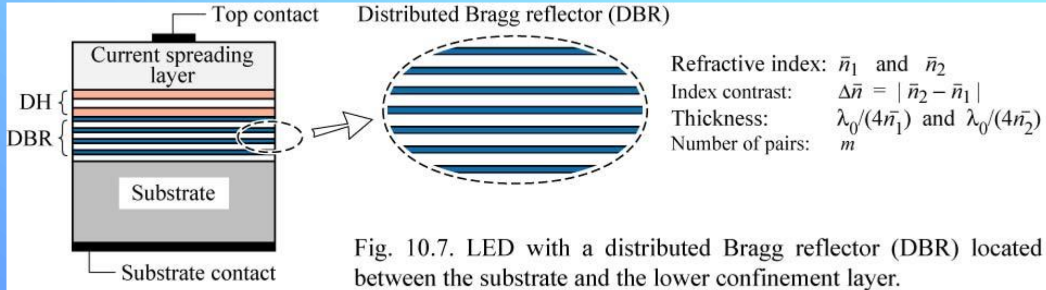


Fig. 10.7. LED with a distributed Bragg reflector (DBR) located between the substrate and the lower confinement layer.

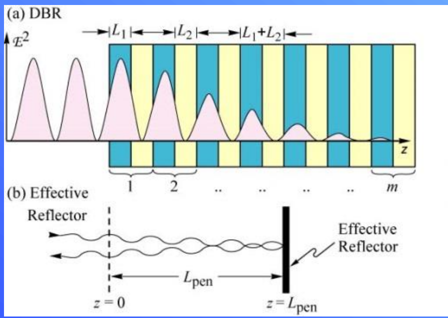


Fig. 10.9. Illustration of the DBR penetration depth. (a) DBR consis-ting of two materials with thickness L_1 and L_2. (b) Ideal (metallic) re-flector displaced from the DBR sur-face by the penetration depth.

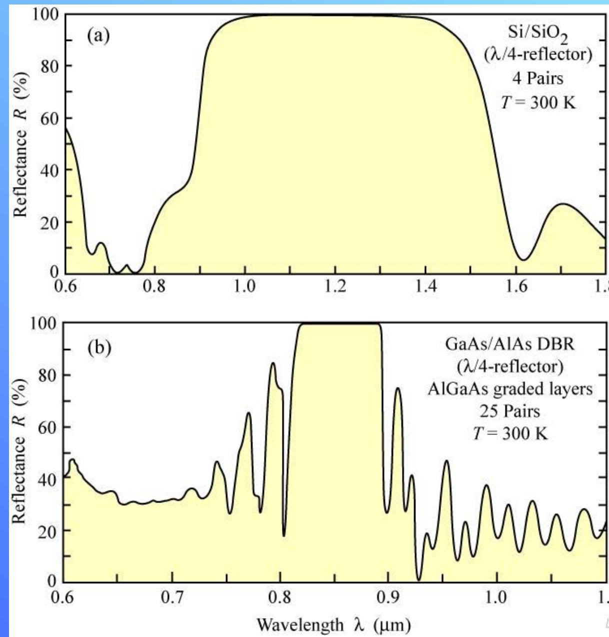


Fig. 10.8. Reflectance of two distributed Bragg reflectors (DBRs) versus wavelength. (a) Four-pair Si/SiO$_2$ reflector with high index contrast. (b) 25-pair AlAs/GaAs reflector. The high-index-contrast DBR only needs four pairs to attain high reflectivity. Note that the stop band of the high-index-contrast DBR is wider compared with the low-contrast DBR.

Resonant Cavity LEDs

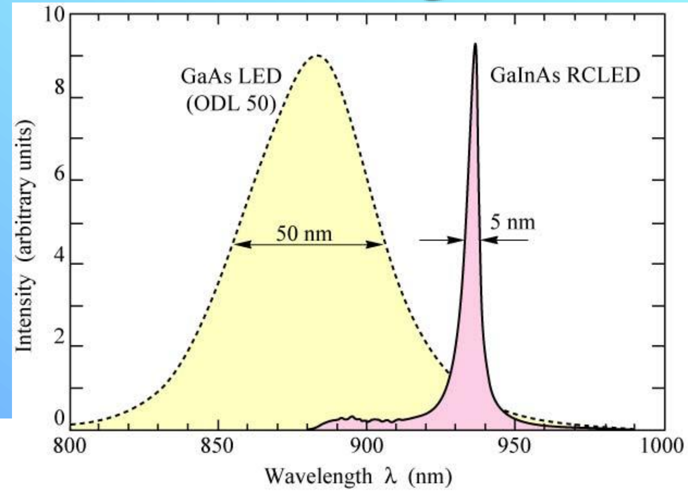


Fig. 15.6. Comparison of the emission spectra of a GaAs LED emitting at 870 nm (AT&T ODL 50 product) and a GaInAs RCLED emitting at 930 nm (after Hunt *et al.*, 1993).

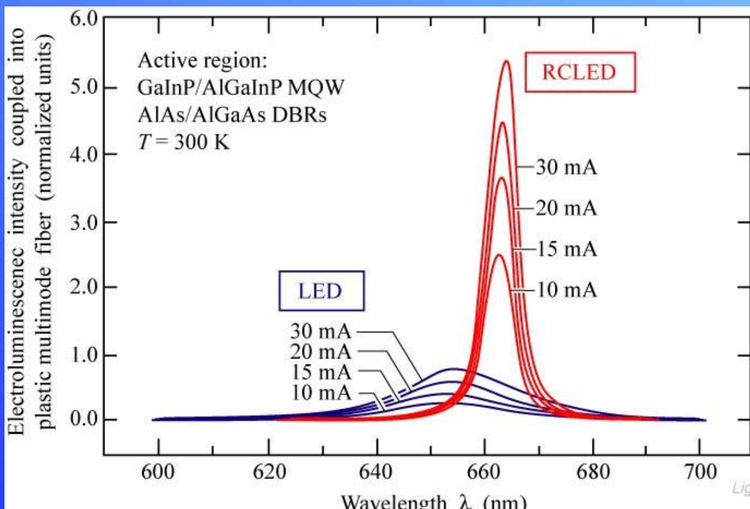


Fig. 15.12. Spectra of light coupled into a plastic optical fiber from an GaInP/AlGaInP MQW RCLED and a conventional GaInP/AlGaInP LED at different drive currents. Note the narrower spectrum and higher coupled power of the RCLED (after Streubel *et al.*, 1998).

Very directional

Excellent for launching into plastic optical fiber for local area networks (LAN) "intraoffice"

Fig. 15.11. AlGaInP/GaAs RCLEDs emitting at 650nm. Note the forward-directed emission pattern similar to that of a semiconductor laser (courtesy of Osram Opto Semiconductors Corporation, Germany, 1999).

Encapsulation

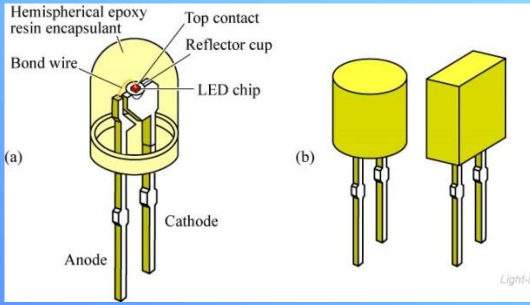


Fig. 11.1. Typical packages; (a) LED with hemispherical encapsulant; (b) LEDs with cylindrical and rectangular encapsulant.

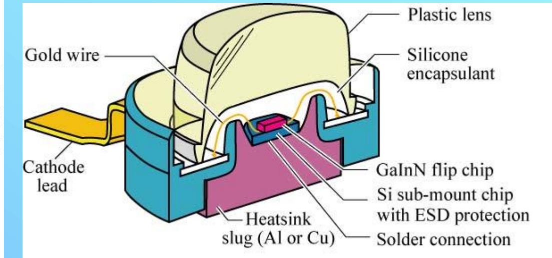


Fig. 11.2. Cross section through high-power package. The heatsink slug can be soldered to a printed circuit board for efficient heat removal. This package is called *Barracuda package* which was introduced by Lumileds Corp. (adopted from Krames, 2003).

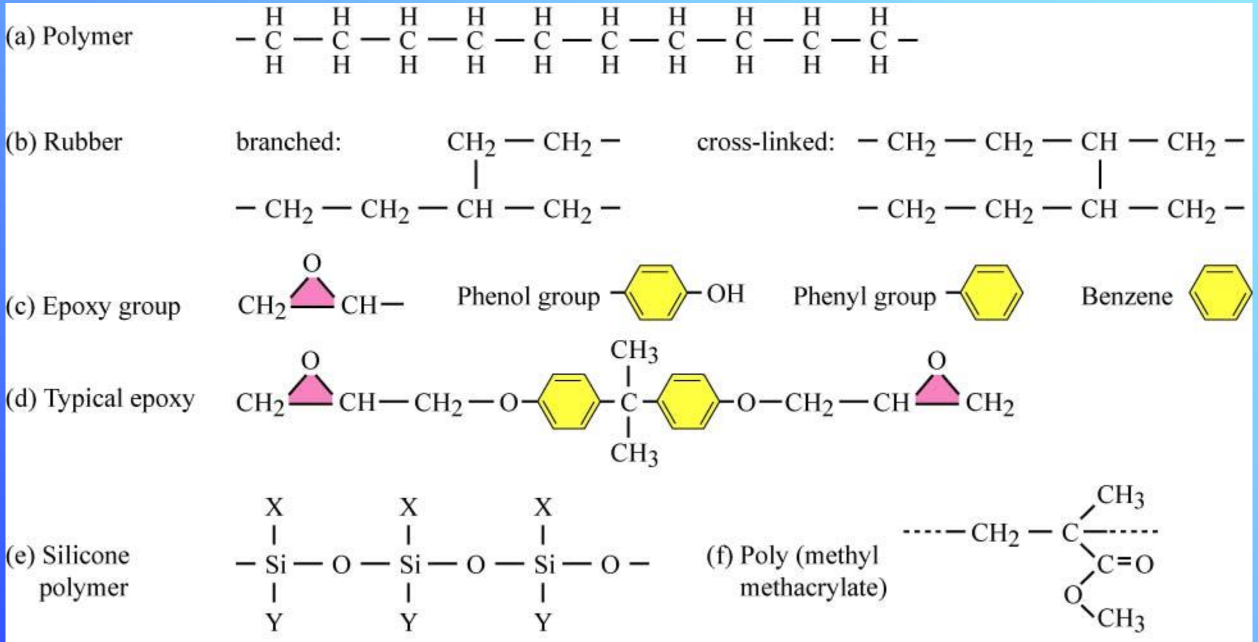


Fig. 11.6. Chemical structures of polymers. Epoxy resins, silicone polymers, and poly methyl methacrylate (PMMA) are used as LED encapsulants. In the silicone structure, X and Y represent atoms or molecules such as H, CH_3 (methyl), C_6H_5 (phenyl).