Solid State Lighting

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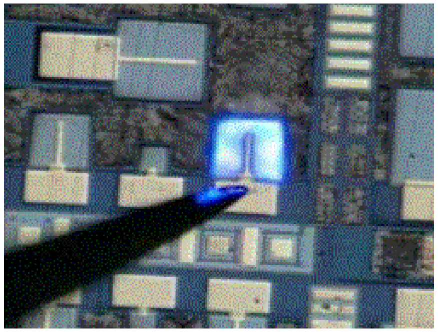
From a torch to Blue and White LEDs
To Solid State Lamps



Blue LED on Si, Courtesy of SET, Inc.

Outline

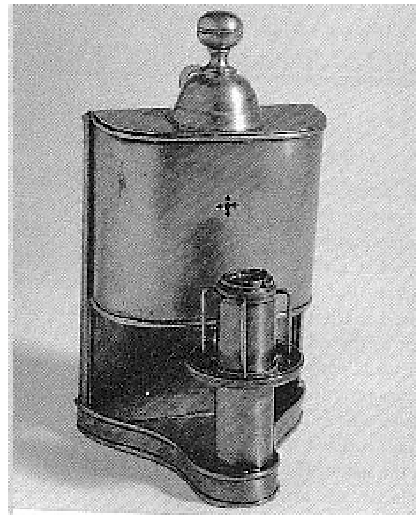
HISTORICAL INTRODUCTION
VISION, PHOTOMETRY AND COLORIMETRY
BULBS AND TUBES
INTRODUCTION TO LIGHT EMITTING DIODES
LIGHT EXTRACTION FROM LEDs
WHITE LED
APPLICATIONS OF SOLID STATE LIGHTING

HISTORICAL INTRODUCTION

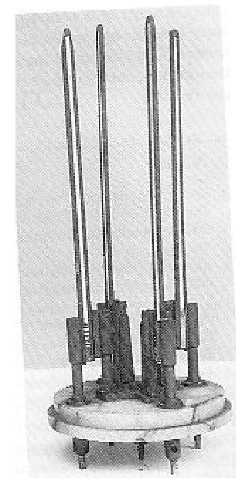
Lighting – prerequisite of human civilization

- 500,000 years ago- first torch
- 70,000 years ago – first lamp (wick)
- 1,000 BC – the first candle
- 1772 - gas lighting
- 1784 Agrand

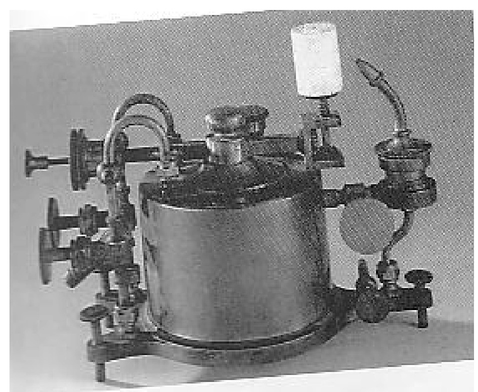
  the first lamp relied on research (Lavoisier)
- 1826 -Limelight - the first solid-state lighting device



Agrand lamp



Yablochkov candle (1876)



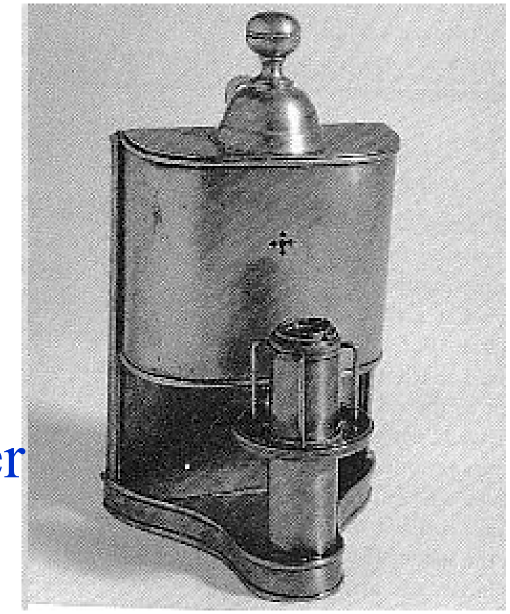
Limelight

Edison bulb (1879)

Agrand Lamp

The design based on the research conducted by A. L. Lavoisier who discovered that combustion is due to oxygen in the air. The lamp was demonstrated to King George III, and Agrand was granted an English patent (No 1425 of 1784).

A tubular wick placed within two concentric tubes and a glass chimney around the burner

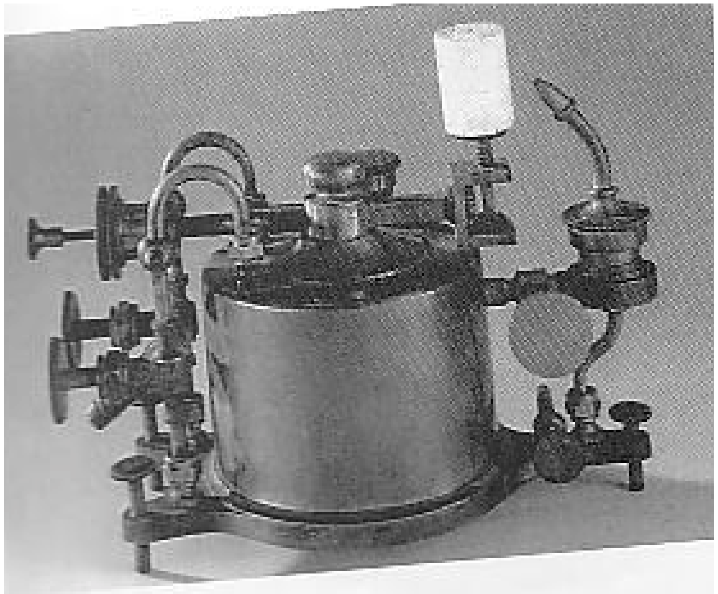


A ten fold gain in light

History of Lighting (continued)

- 1772 - gas lighting introduced by Scottish inventor William Murdoch
- Limelight - the first solid-state lighting device (introduced by Thomas Drummond in 1826)

Cylinder of lime (calcium oxide)
brought to a state of dazzling brilliancy
by the flame of the oxy-hydrogen blowpipe



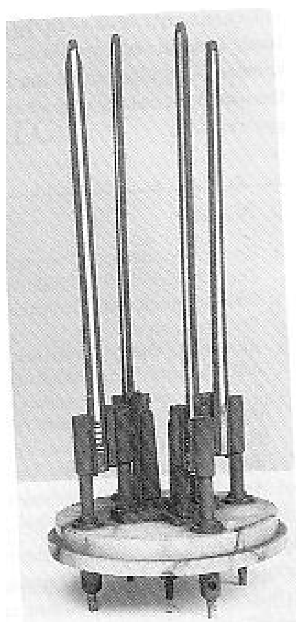
Candoluminescence and Gas Mantle

- The emission was due to a– candoluminescence - discovered by Goldsworthy Gurney in 1820.
- Candoluminescence is caused by thermal excitation of ions, which emit in excess of black body incandescence
- Limelight was used in theaters in the 1860’s and 1870’s until superseded by the electric arc.
- In 1886, the candoluminescence-based the gas mantle – a fabric of cotton soaked in a solution of a metallic salt (a mixture of cerium oxide and thorium oxide with a ratio 1:99 heated by high temperature non-luminous flame from the Bunsen burner light source
- Invented by by Auer von Welsbach and used widely in the first third of the 20th century
- It still can be found in kerosene and gas lamps.

The Dawn of Electric Lighting

- 17-th century, effect of the luminous discharge of static electricity in mercury vapor was discovered
- Beginning of the 19th century, Sir Humphry Davy demonstrated a discharge between two rods of carbon (an arc) and a glowing of a piece of wire heated by electric current (incandescence).
- He used a battery made of 2000 pairs of copper and zinc elements invented by Alessandro Volta in 1800.
- The change from flame to electric power in lighting technology happened only in 1870's, when Z. T. Gramme introduced an efficient continuous-current generator (dynamo).

Yablochkov candle (1876). The first electric lighting device.



Thomas Alpha Edison bulb (1879)

First LED (1907)

FEBRUARY 9, 1907. ELECTRICAL WORLD.

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.

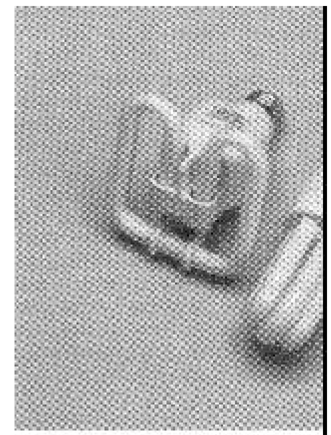
NEW YORK, N. Y. H. J. ROUND.

History of Electric Lighting in a nut shell

- 1876. Pavel Yablochkov fabricated the first practical electric lighting device
- 1879. Thomas Alva Edison Edison demonstrated his lamp
- 1897. Nernst developed a filament made of cerium oxide-based solid electrolyte.
- 1900. Peter Cooper Hewitt patented the mercury vapor lamp. 1903. A. Just and F. Hanaman developed tungsten filament
- 1904. C. O. Bastian and A. E. Salisbury combined the mercury vapor lamp with a low-temperature incandescent lamp
- 1904. Moor introduced discharge lamps using air
- 1907 Round reports on the first LED (SiC)
- 1910. P. Claude filled discharge lamps with inert gases
- 1938. GE and Westinghouse Electric Corporation put on the market the new colored and white fluorescent lamps.

Lighting in 2001

- Residential lighting - tungsten incandescent lamps (Or a compact fluorescence lamp (CFL) with higher efficiency)



- Work environments - fluorescence lamp
- Street lighting – ugly sodium lamp.
- **However, all this is about to change because of explosive development of high brightness visible Light Emitting Diodes**

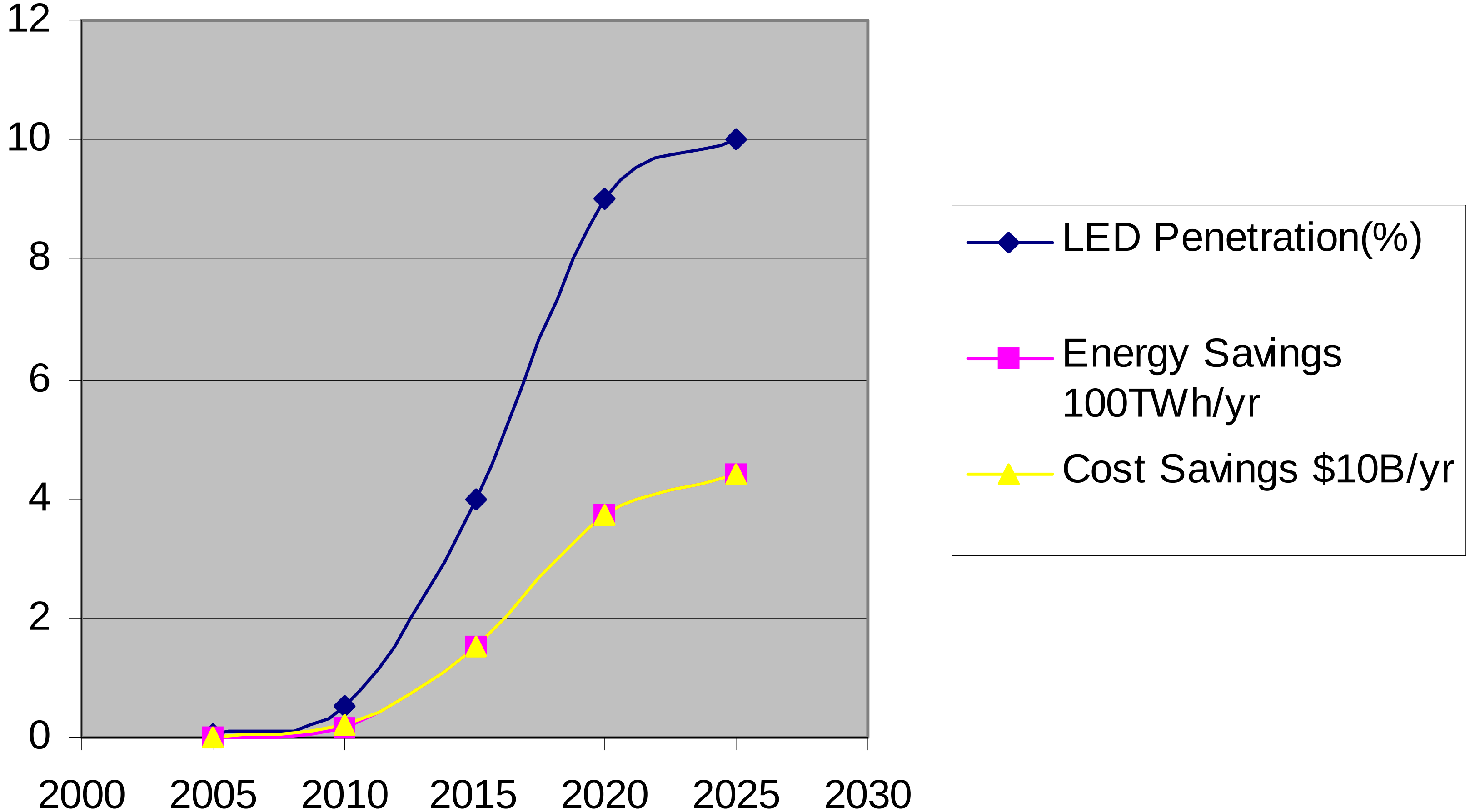
LIGHTING ECONOMY

Importance of Solid State Lighting

- 21% of electric energy use is in lighting
- Half of this energy can be saved by switching to efficient and cold solid-state lighting sources
- Projected financial savings from solid-state lighting might reach $115 billion by year 2020
- Solid-state lighting will use visible and UV LEDs that are expected to reach lifetimes exceeding 100,000 hours
- At present, LEDs are the most efficient sources of colored light in almost entire visible spectral range.
- White phosphor-conversion LEDs already surpassed incandescent lamps in performance

Benefits of LED Lighting

An improvement of luminous efficiency by 1% may save 2 billions dollars per year.



"Low Investment Model"

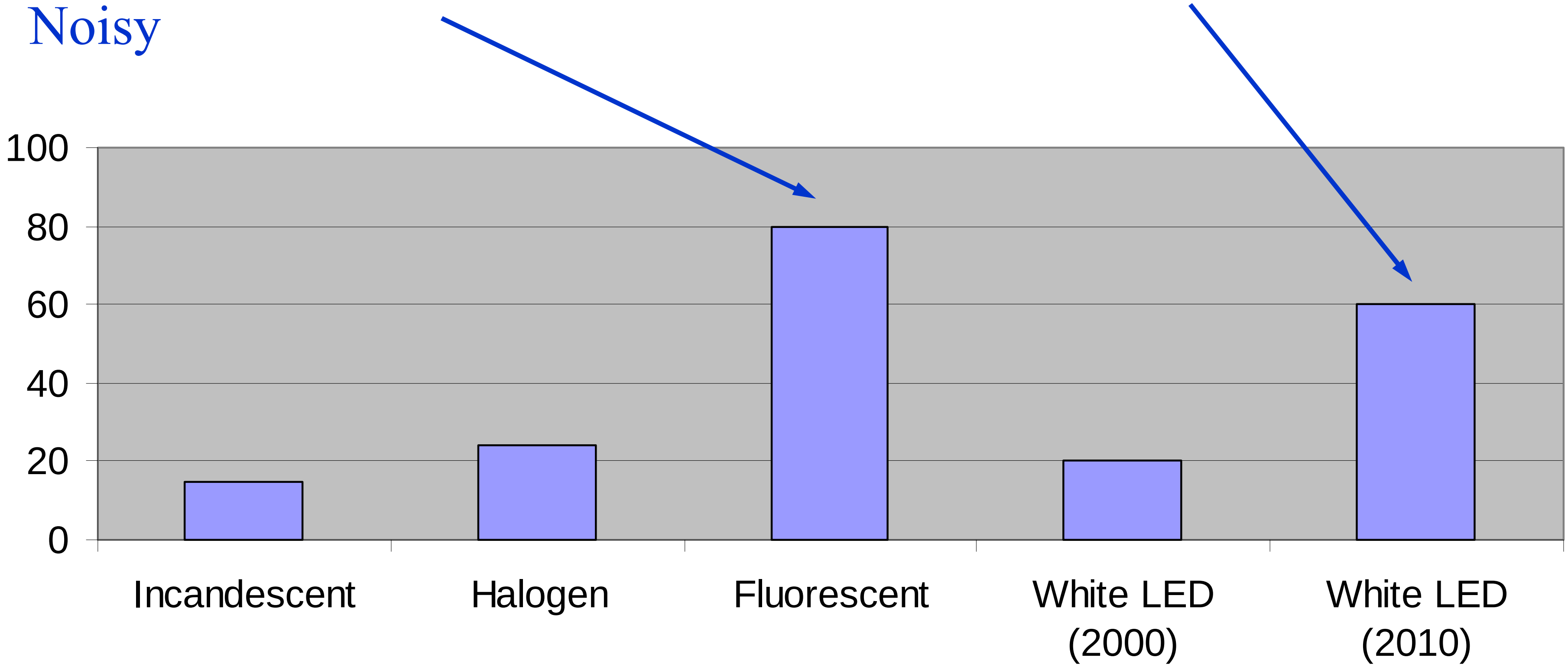
Data from R. Haitz, F. Kish, J. Tsao, and J. Nelson
Innovation in Semiconductor Illumination: Opportunities for National Impact (2000)

Solid State Lighting

Flickers
Cannot be dimmed
Losses in ballast
Noisy

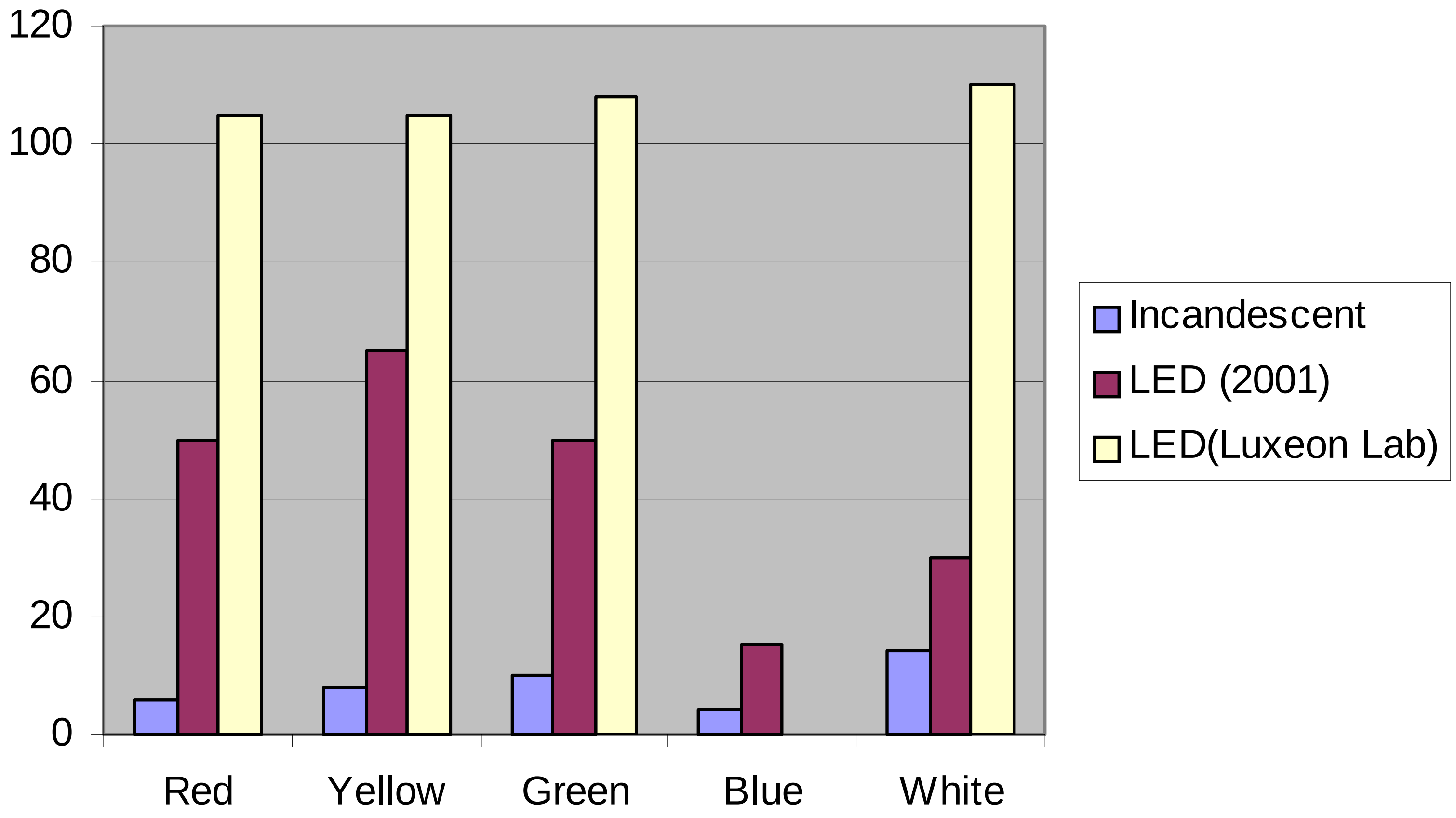
Efficiency (lm/W)

Good!

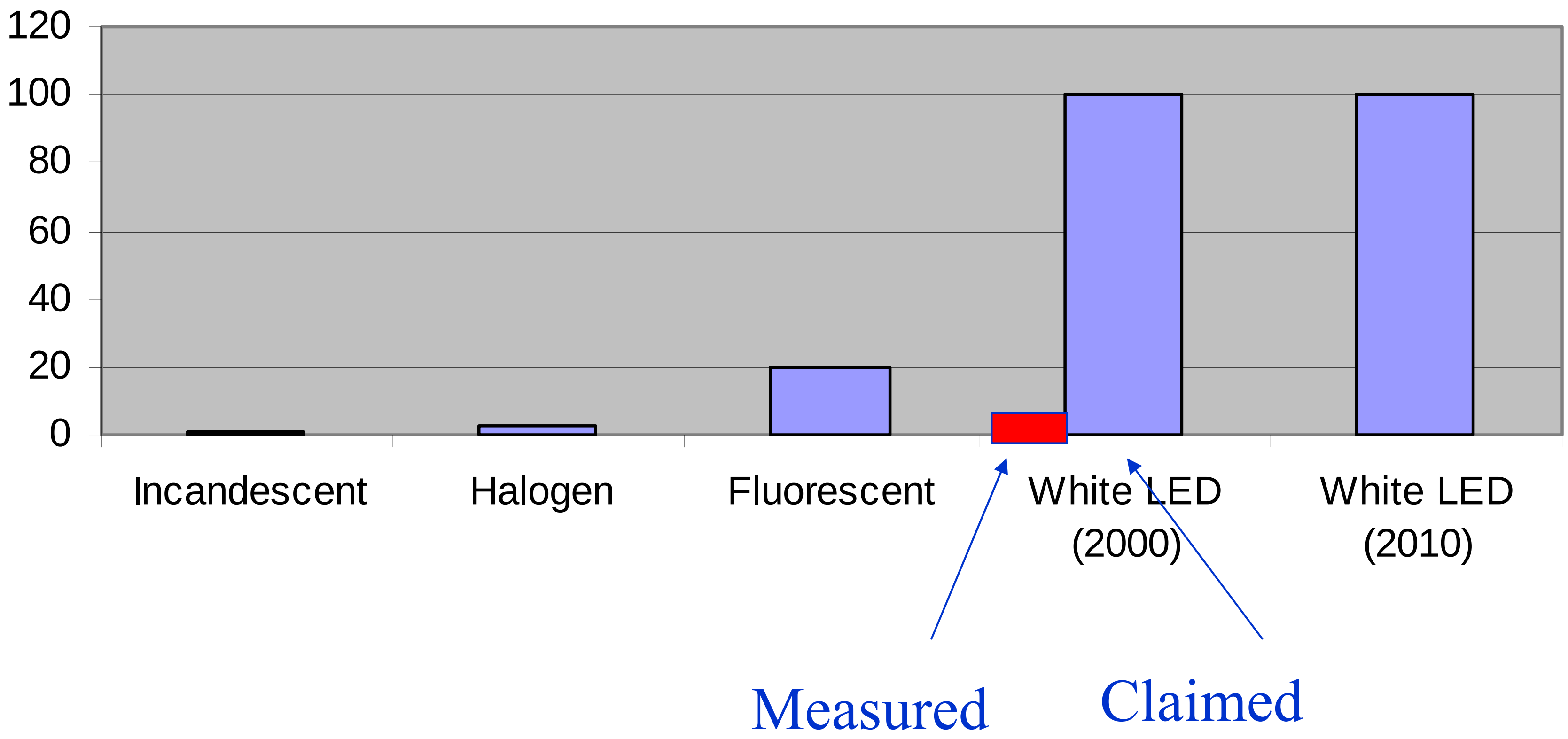


Solid State Lighting

Luminous efficiency lm/W



Solid State Lighting:
Lifetime (in thousands of hours)



From Introduction to Solid State Lighting A. Zukauskas, M. S. Shur, and R. Gaska,

Challenges of Solid State Lighting

- **Improve efficiency of light generation**
- **Improve efficiency of light extraction**
- **Improve quality of light**
- **Reduce COST**

C'_L

Cost of light

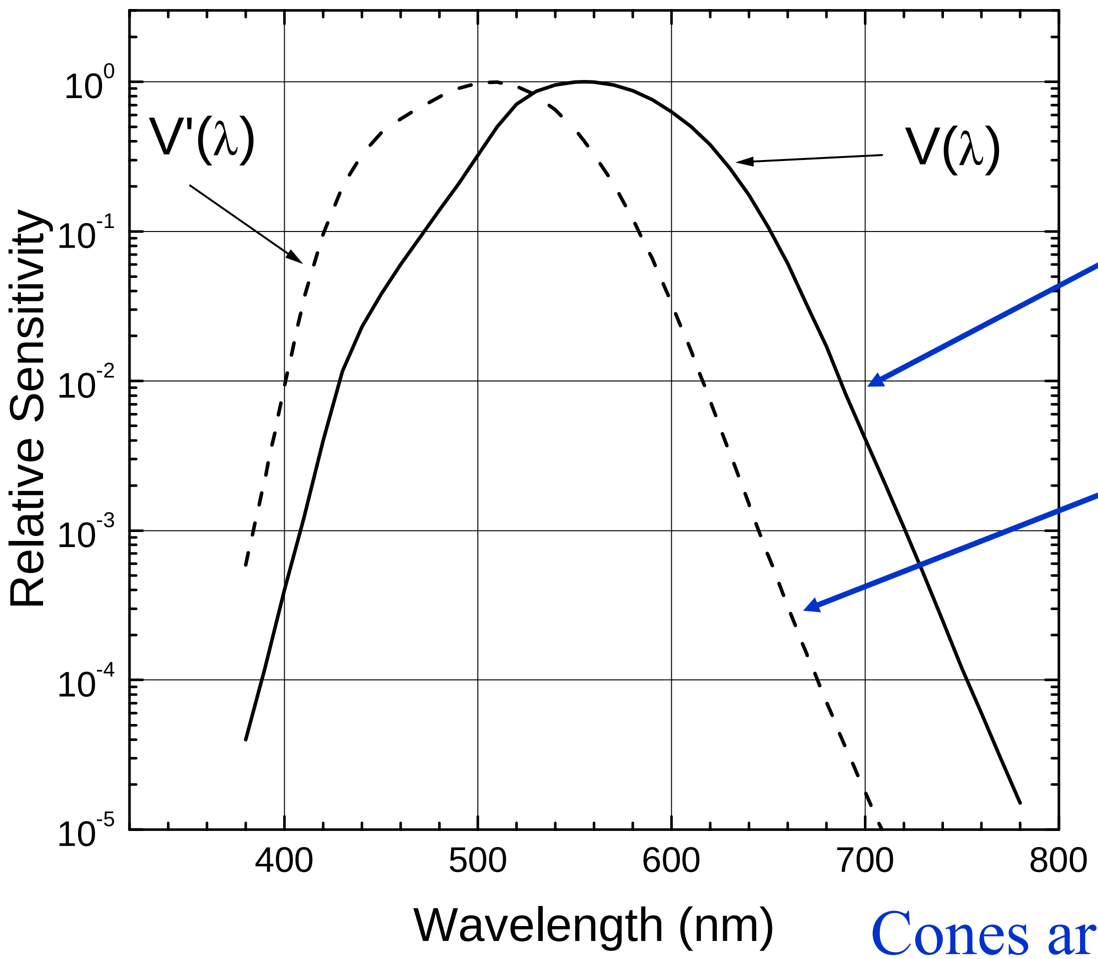
- Estimated from the cost of the lamp and the electric power consumed divided by the amount of lumens produced over the lifetime. For 1 Mlm·h, this yields a cost

$$C_{1Mlmh} \approx 10^6 \frac{C'_L}{P_L \tau_L \eta'_L} + 10^3 \frac{C_{1kWh}}{\eta'_L}$$

C'_L is the cost of the bulb
C_{1kWh} is the price of 1 kW·h power
η'_L is the luminous efficiency
P_L is the wattage
τ_L the lifetime of the lamp

VISION, RADIOMETRY, PHOTOMETRY AND COLORIMETRY

Eye sensitivity



Photopic vision (cones)
@ High Illumination

Scotopic vision (rods)
@ Low illumination

Cones are red, green, and blue

Radiometry and Photometry

Watt

W/nm

Photopic vision eye sensitivity

$$\Phi_v = 683\ \mathrm{lm/W} \times \int \Phi_e\, V(\lambda)\, d\lambda$$

Luminous flux

W/nm

Wavelength (nm)

$$I_v = d\Phi_v / d\omega = 683\ \mathrm{lm/W} \times \int I_e\, V(\lambda)\, d\lambda$$

Luminous intensity
(Candela = lm/sr – SI unit)

1/60 of the luminous intensity per square centimeter of a blackbody radiating at the temperature of 2,046 degrees Kelvin

Luminous efficiency: power into actuation of vision (lm/W)

Luminance

- The concept of luminous intensity is not directly applicable to an extended source of light
- Such sources are described by luminance, which is the quotient of the luminous flux propagating from an element of the surface and observed at an angle per unit solid angle
- The luminance is measured in candelas per square meter (cd/m2).
- Scotopic vision dominates at luminance below 10^{-2} cd/m^2
- Above 10 cd/m^2 the vision is completely photopic.
- The sun viewed from the sea level exhibits the average luminance of 1.6×10^9 cd/m^2, and the luminance of the moon is approximately 2500 cd/m^2.

Illuminance

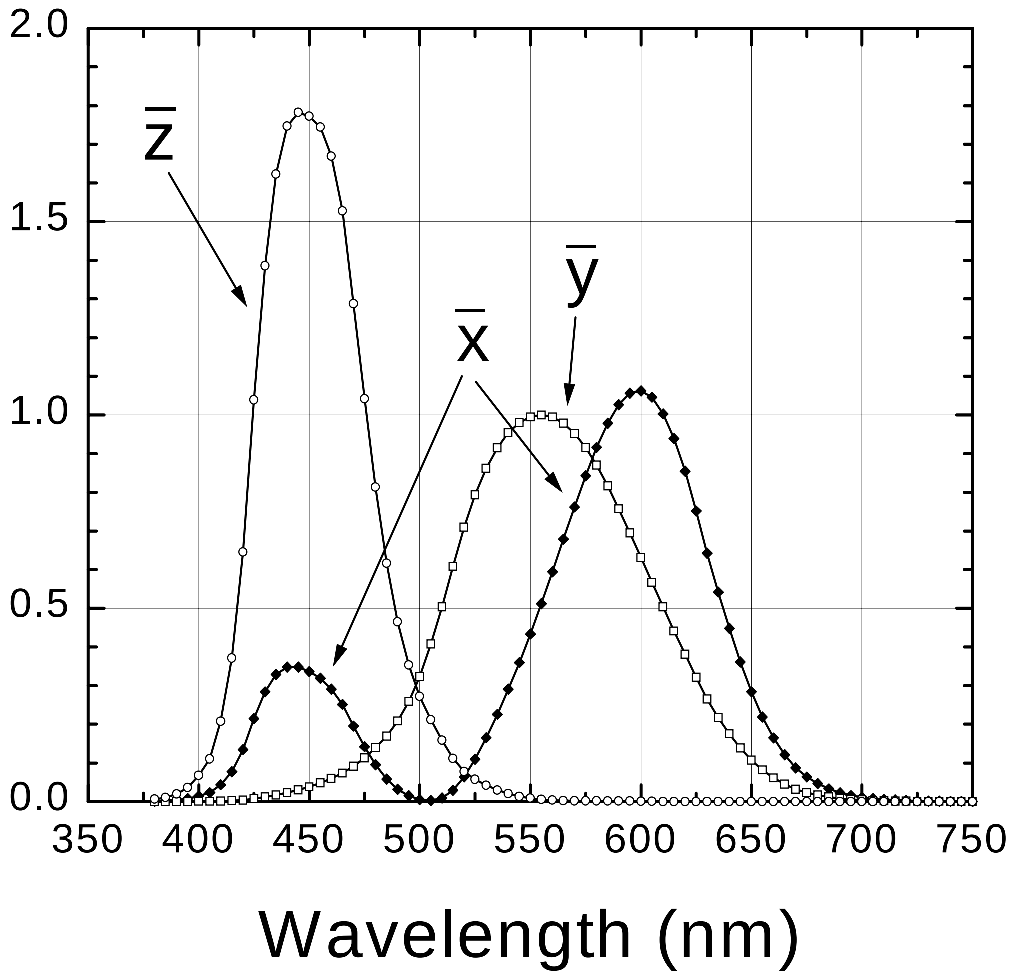
- The measurement unit for illuminance is lumen per square meter, also called lux (lx).
- Sun generates the illuminance on the earth's surface from 104 lx to 105 lx depending on cloudiness; the illuminance by the moon does not exceed 0.1 lx.
- The higher is the illuminance, the higher is the ability of the eye to distinguish details, small contrasts and color hues. Therefore, different activities require different levels of illuminance.

How much light do you need?

Type of Activity	Illuminance ($lx = lm/m^2$)
Orientation and simple visual tasks (public spaces)	30-100
Common visual tasks (commercial, industrial and residential applications)	300-1000
Special visual tasks, including those with very small or very low contrast critical elements	3,000-10,000

Colorimetry

1931 CIE color matching functions: "purple" , "green" , and "blue"



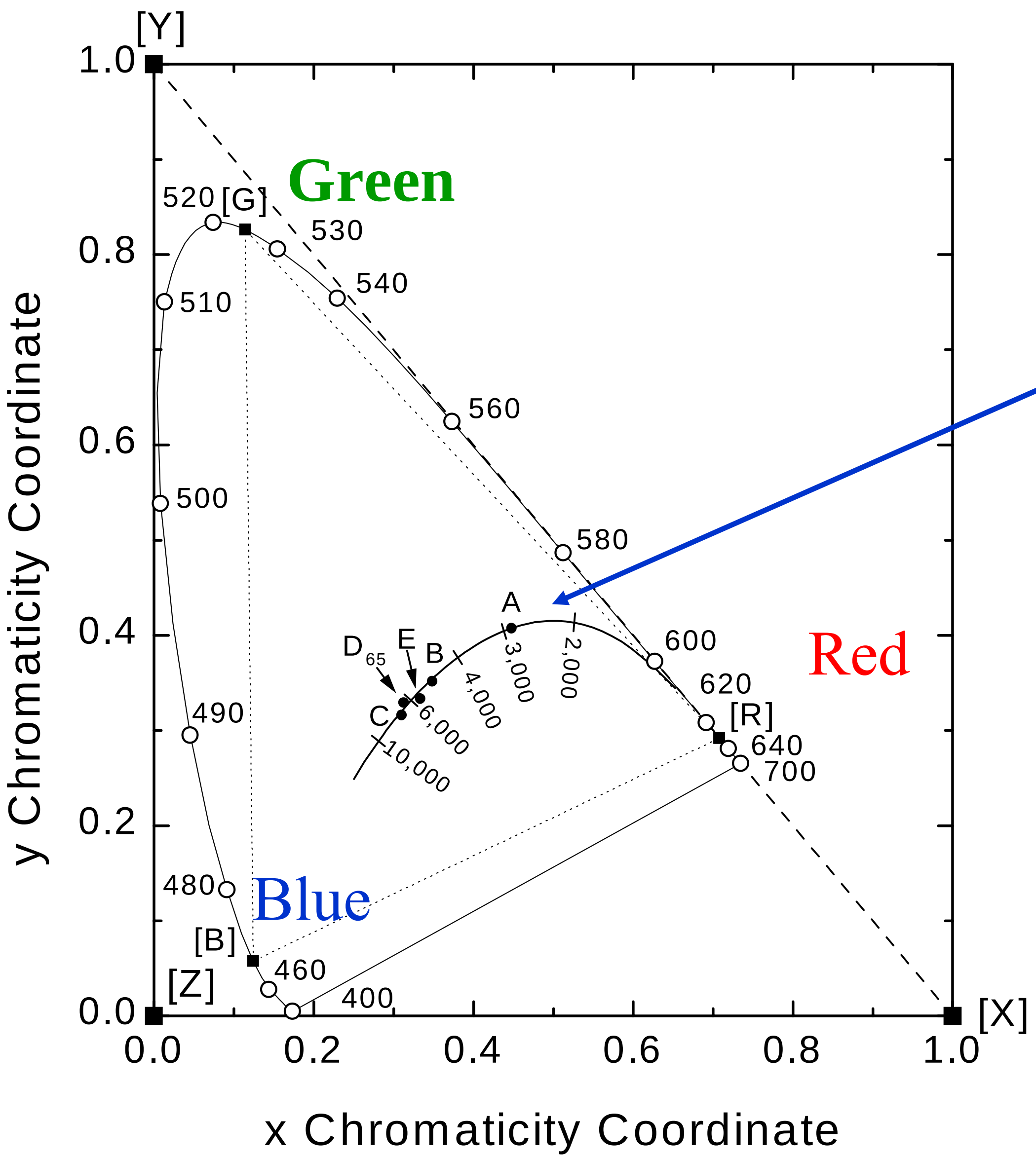
Chromaticity coordinates
Color temperature
Color rendering

$$X = \int \bar{x}(\lambda)\, S(\lambda)\, d\lambda$$

$$Y = \int \bar{y}(\lambda)\, S(\lambda)\, d\lambda$$

$$Z = \int \bar{z}(\lambda)\, S(\lambda)\, d\lambda$$

Color Coordinates



Is it really that bad?
Just remember:
White is black!

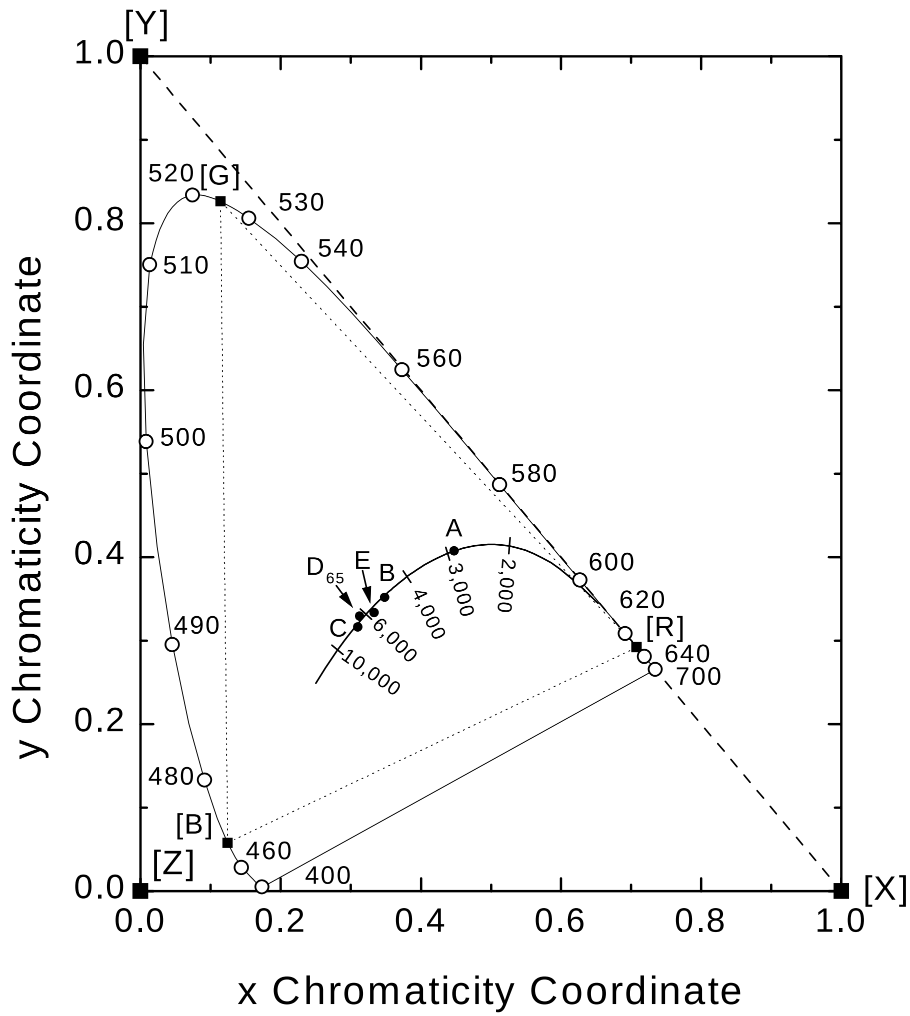
Planckian locus
(black body radiation)

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

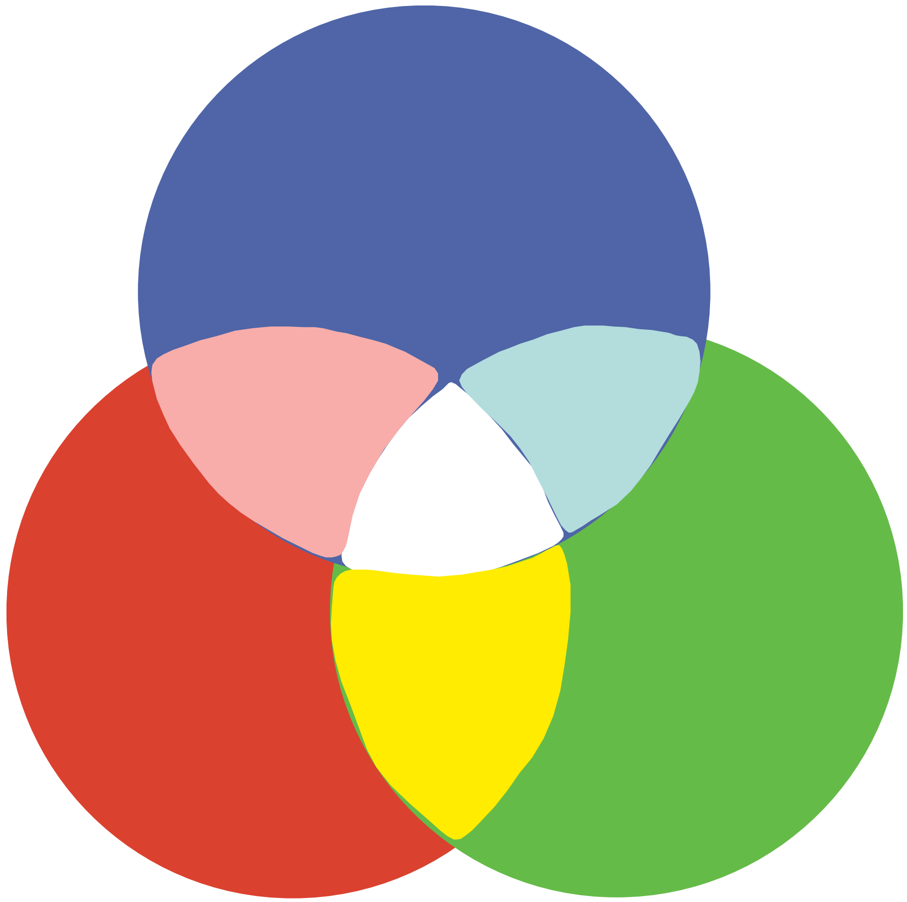
Standard CIE Sources

- A (tungsten at 2856 K)
- B (direct sunlight, approximately 4870 K)
- C (overcast sunlight 6770 K
- D65 (daylight, 6504 K)
- Point E marks equal energy (,).

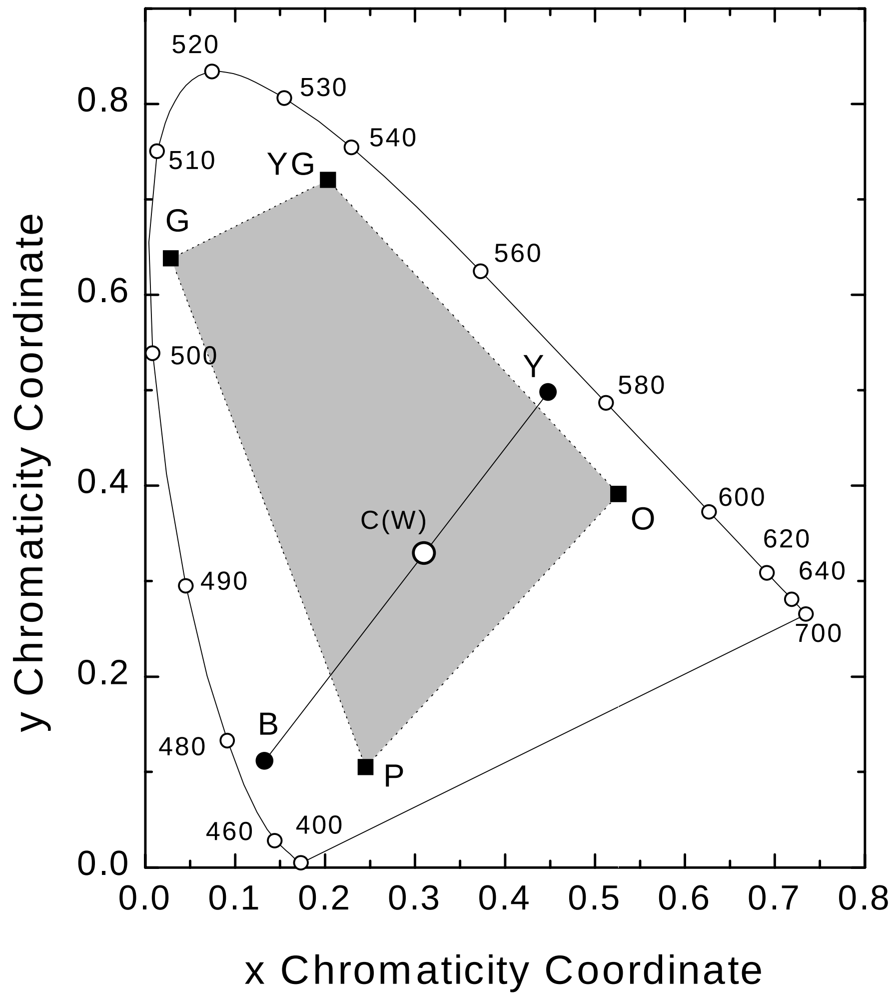


Color Mixing

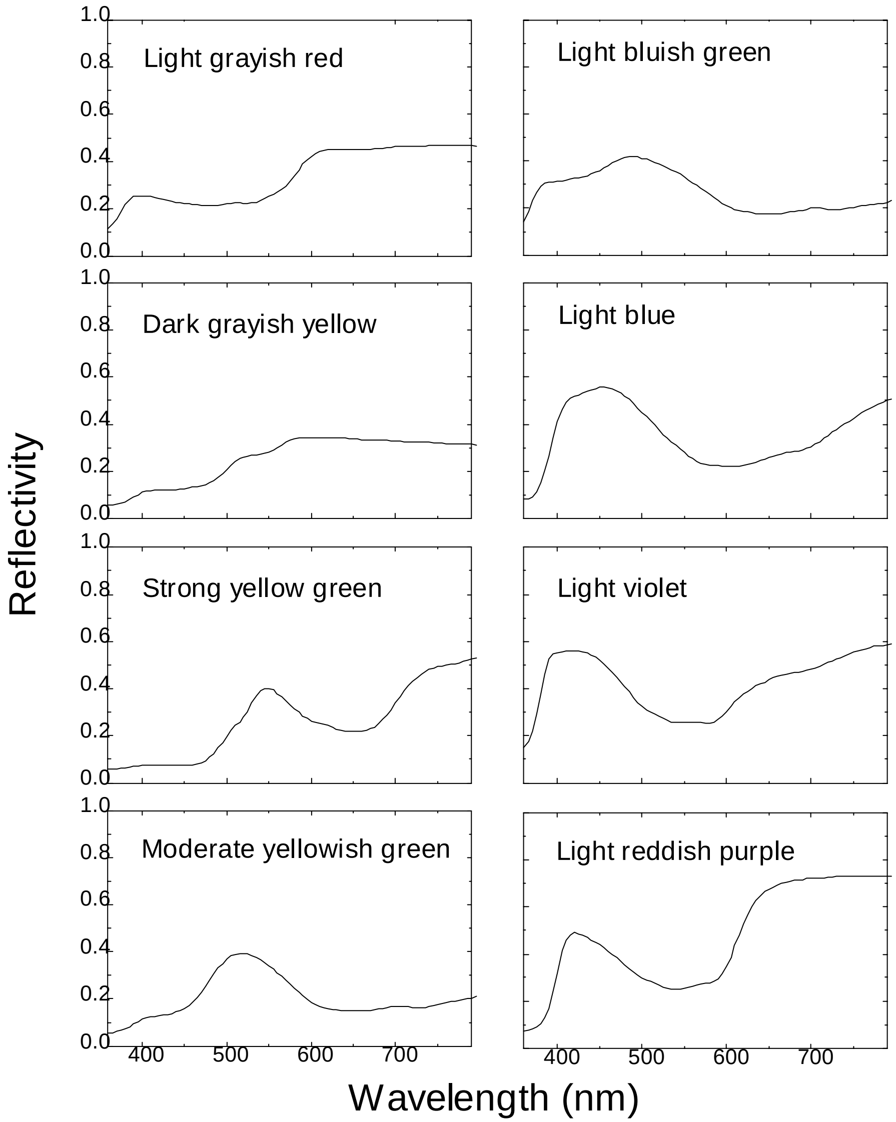
•Red, green, blue appear as white
•Red and blue appear as magenta
•Green and blue give cyan
•Red and green give yellow



Color Mixing in CIE 1931 Diagram



Color Rendering



General Color Rendering Index

R_a (CRI)

integrates the reflectivity data for 8 specified samples

Special color rendering indices, refer to six additional test samples

R_a varies from up to 100

100 is the best. It might be negative

From Introduction to Solid State Lighting A. Zukauskas, M. S. Shur, and R. Gaska,

Math of Color Rendering (for reference only)

Reference source

$$S_r(\lambda) \rightarrow S_r(\lambda)\,\rho_i(\lambda), \; i = 1,\ldots,8$$

Test source

$$S_k(\lambda) \rightarrow S_k(\lambda)\,\rho_i(\lambda), \; i = 1,\ldots,8$$

USC chromaticity coordinates

$$u = 4x/(-2x + 12y + 3)\,, \; v = 6y/(-2x + 12y + 3)$$

General color rendering index (CRI)

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i$$

Where Ri is

$$= 100 - 4.60 \left\{ \left[W_{ki} - W_{ri} \right]^2 + 13^2 \left[W_{ki} \left(u'_{ki} - u_r \right) - W_{ri} \left(u_{ri} - u_r \right) \right]^2 + 13^2 \left[W_{ki} \left(v'_{ki} - v_r \right) - W_{ri} \left(v_{ri} - v_r \right) \right]^2 \right\}^{1/2}.$$

$$W = 25Y^{1/3} - 17$$

$$c = \left(4 - u - 10v\right)/v$$

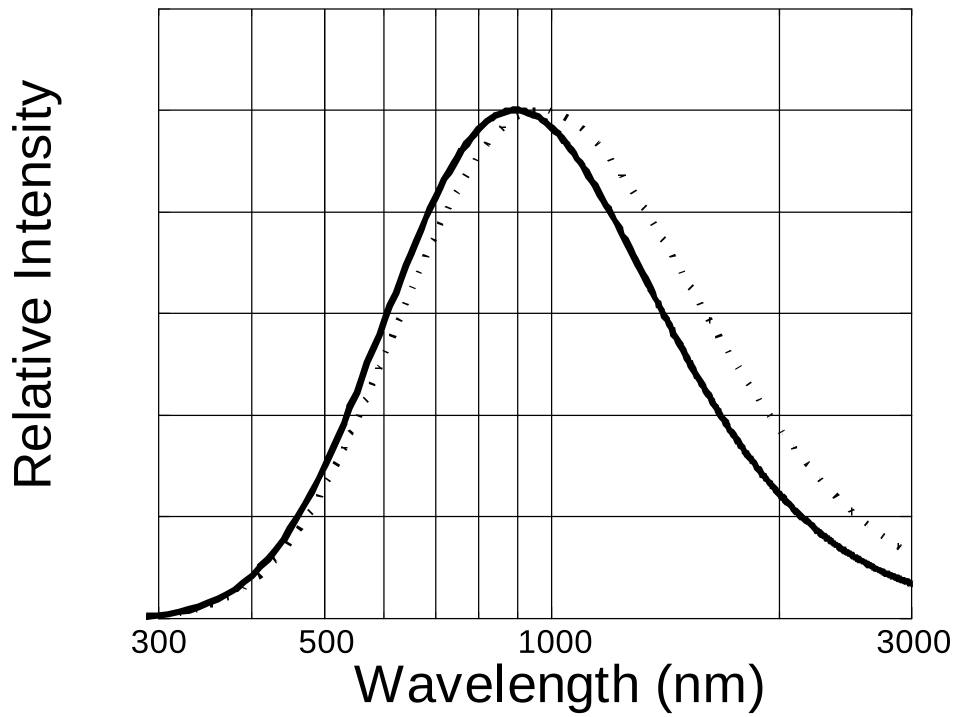
$$d = \left(1.708v + 0.404 - 1.481u\right)/v$$

$$u'_{ki} = \frac{10.872 + 0.404\, c_r c_{ki} / c_k - 4\, d_r d_{ki} / d_k}{16.518 + 1.481\, c_r c_{ki} / c_k - d_r d_{ki} / d_k}$$

$$v'_{ki} = \frac{5.520}{16.518 + 1.481\, c_r c_{ki} / c_k - d_r d_{ki} / d_k}$$

BULBS AND TUBES

Normalized emission intensity of the black body (dotted line) and tungsten radiator (solid line) at 3000 K



At present, tungsten incandescent lamps serve most of the needs of residence lighting.

Incandescent Bulb - A True Challenge

- filament is wound into a helix to reduce the heat conducted into surrounding gas
- further reduction of gas loss is achieved by secondary coiling of the primary coil
- filament is supported by molybdenum wires and electrically connected to the leads made from nickel or nickel-plated wires.
- The design usually comprises a copper-nickel fuse
- The bulb is made of soda-lime silicate glass and the cap is made of aluminum or brass.
- Matching of the thermal expansion and stability of the glass-metal seal is provided by Dumet wires (
- bulb is filled with high-atomic-weight inert gas (argon and, rarely, krypton).
- nitrogen is used to prevent formation of an arc during the filament failure.
- To reduce blackening of the bulb, some getter is added for absorption of any remainder of oxygen and moisture.
- To diffuse and to direct the light, inside frosting and integral reflectors are used
- Plus marketing for a total cost of 50 cents

Tungsten Halogen Lamps

- If the tungsten evaporation rate is reduced, the filament of the incandescent lamp might operate at higher temperature, and the lifetime of the lamp may increase.
- The addition of a halogen to the gas filling is known to establish a chemical transport cycle, in which tungsten forms halides when diffusing from the hot filament towards the cooler wall.
- Tungsten halides diffuse in the opposite direction and dissociate at the filament. The transport cycle results in nearly zero concentration of the tungsten at the bulb wall and in an increased concentration at the filament.
- As a result, filament temperatures as high as 3450 K can be achieved, with a consequent improvement in efficiency.

FLUORESCENT LAMPS

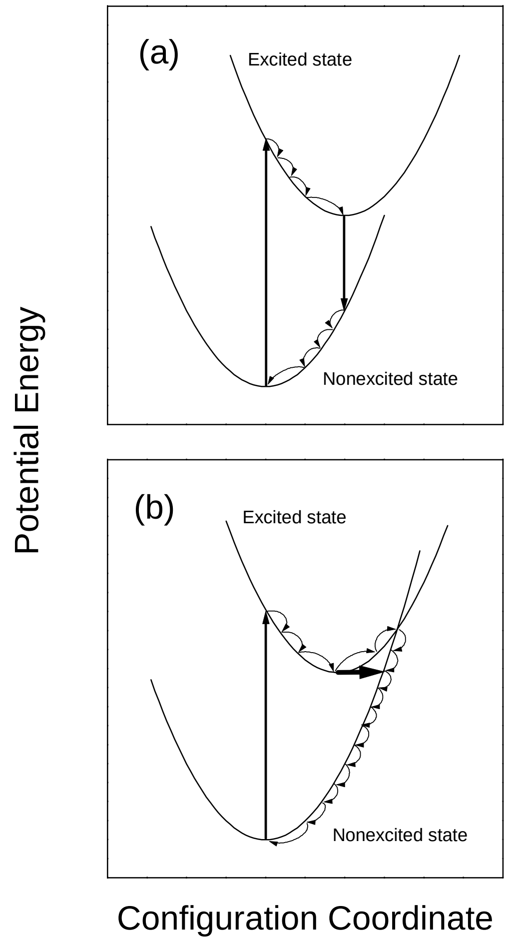
- When a large enough electric field is applied to a gas, the gas breaks down and partially ionizes. The resulting conductive plasma comprises electrons as well as a mixture of ionized and neutral particles, some of which are excited

- By limiting the electric current limitation (by introducing a ballast in the circuit), the discharge is prevented from avalanche ionization and stabilized. The fluorescent lamps utilize low-pressure discharge, in which electrons are accelerated to effective temperatures typically of 11,000-13,000 K, while ions remain almost in thermal equilibrium with the environment (≈310 K).

FLUORESCENT LAMPS (cont)

- Fast electrons inelastically relax by exciting atoms, molecules and ions, which might emit light.
- At present, two efficient low-pressure discharge emitters are utilized – vapors of mercury and sodium.
- Sodium emits yellow light, which is directly used, mostly for street lighting
- At low pressures, the major part of the emission from mercury atoms is in UV owing to the radiative transition from the excited 3P1 state to the ground state (4.886 eV/253.7 nm).
- In a fluorescent lamp, visible radiation is produced by photoluminescence in phosphors, which are deposited on the wall of a tubular bulb. UV photons reach the wall via radiative transport, i. e. by multiple reabsorption and reemission by other mercury atoms.

Configuration-coordinate diagrams of activator phosphor ion for radiative (a) and nonradiative (b) conversion processes



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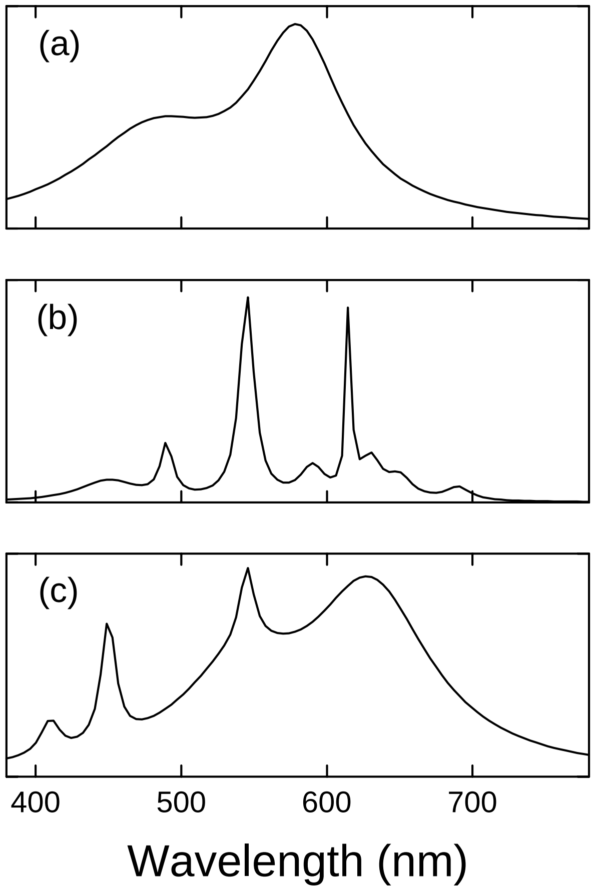
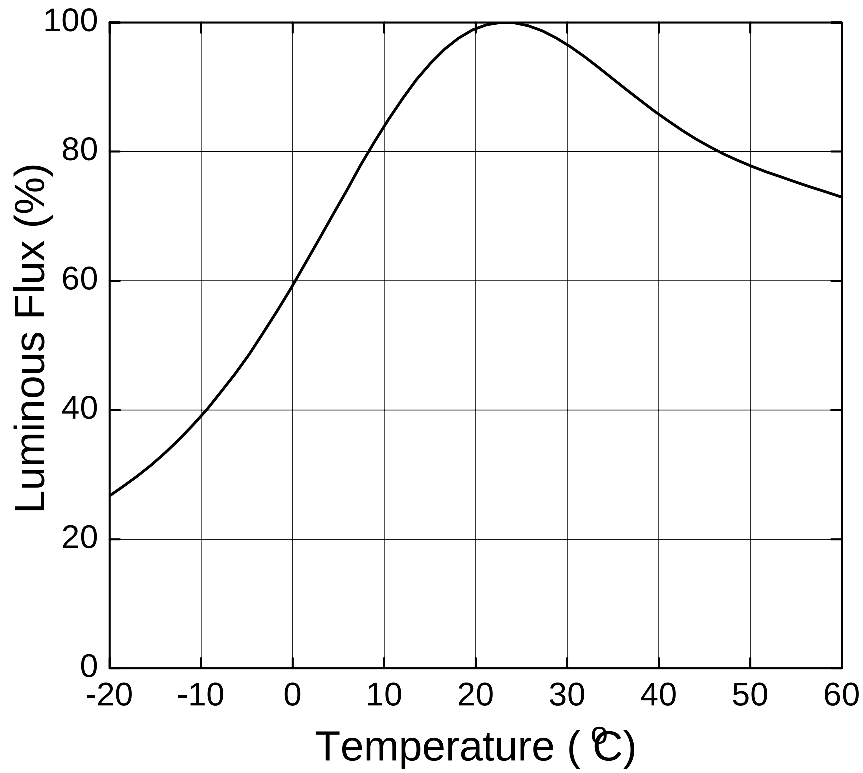
Spectral power distributions of typical fluorescent lamps. (a) halophosphate, (b) triphosphor blend, (c) multiband phosphor.



Light output of a typical fluorescent lamp as a function of ambient temperature



Optimized for room temperature

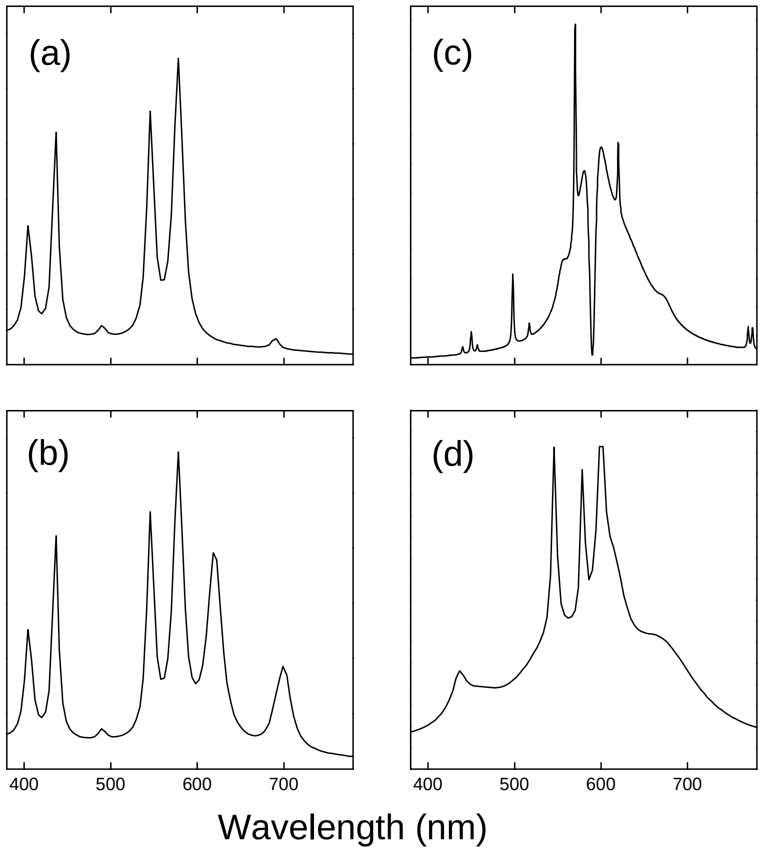
LOW-PRESSURE SODIUM LAMPS

- Since the luminous efficacy of the D-line is about 530 lm/W, the theoretical efficiency of the LPS lamp is extremely high. Despite that 60-80% of the power is wasted for infrared radiation and heat losses, the luminous efficiencies (100-200 lm/W) are the highest among present practical lamps.
- The wattage of the marketed LPS lamps is from 18 to 180 W with the light outputs ranging from 1,800 to 33,000 lm.
- The failure is due to deterioration of cathodes and typical lifetimes are 14,000-18,000 hours.
- The main disadvantage of the LPS lams is a very poor color rendering.

HIGH-PRESSURE DISCHARGE LAMPS

- Heavy particles (atoms and ions) are heated almost to the same temperatures as the electrons, owing to the high rate of elastic collisions. At pressures of around 1 atmosphere, the temperature of the plasma is typically in the range of 4,000-6,000 K.
- Most of the light is generated in the hot center of the arc. However, because of the temperature gradient, heat flows out of the center decreasing the radiative efficiency to approximately 60%.
- High pressure leads to collision broadening of the line spectra. The resulting wide emission bands considerably improve the color rendering of the light.

Typical power-distribution spectra of high-pressure discharge lamps.



(a) Clear mercury lamp, (b) improved-color (phosphor-coated) mercury lamp, (c) sodium lamp, (d) metal halide lamp with rear earth (Dy/Ho/Tm)-Na-Tl dose

Metal Halide Lamps

- Luminous efficiency and color rendering of the high-pressure mercury discharge lamp may by considerably improved by introducing metal halides
- As soon as the tube wall reaches sufficient temperature, a metal halide evaporates and starts a transport cycle
- At the hot core of the discharge, the halide dissociates and produces metal atoms that contribute to the emission. When the metal atoms diffuse towards the cooler region at the wall, they recombine with the halogen to form the halide, which does not react with the wall material.
- The operation pressure of the additive metals is in the range of 10-100 torr (1300-13,000 Pa). Although this pressure is small in comparison with the pressure of mercury (typically 1-20 Atm), the additive metals produce a considerable part of light because their excitation energy (around 4 eV) is lower than that of mercury (7.8 eV).

Applications

- Diverse wattage, dimensions, and other specification
- High brightness and good color rendering characteristics make them applicable for general lighting services in offices, supermarkets, large stores, and in a lot of industrial and social environments
- High-luminosity units are indispensable for floodlights
- Low-power short-arc MH lamps gave birth to new kind of economic, precise, small-dimension, and long lifetime vehicle headlights.

Parameters of practical lamps and tubes

Type	Wattage (W)	Luminous flux init (avrg) (lm)	Eff-cy (lm/W)	R_a	CCT (CT) (K)	Life-time (hours)	1 Mlm·h price ($)
Incandescent (120 V)	60	865	14.4	100	(2790)	1,000	7.4
Tungsten halogen (120 V)	50	590	11.8	100	(2750)	2,000	12
Fluorescent triphosphor	32	2,850 (2,710)	84	78	4100	24,000	1.6
Compact fluorescent	15	900 (765)	51	82	2700	10,000	3.9
Low-pressure sodium	90	12,750 (11,095)	123	- 44	1800	16,000	1.6

Parameters of practical lamps and tubes (cont.)

Type	Wattage (W)	Luminous flux init (avrg) (lm)	Eff-cy (lm/W)	R_a	CCT (CT) (K)	Lifetime (hours)	1 Mlm·h price ($)
High-pressure mercury	250	11,200 (8,400)	34	50	3,900	24,000	3.8
High-pressure Sodium	250	28,000 (27,000)	108	22	2100	24,000	1.3
Metal halide	400	36,000 (24,000)	60	65	4,000	20,000	2
Induction	55	3,500 (2,800)	64	80	3,000	100,000	2
Microwave sulfur	1,425	135,000	95	79	5,700	20,000	?

BASICS OF ALL-SOLID-STATE LAMPS

Efficiency and Efficacy

Radiant efficiency: measure of light source ability to convert the consumed power P into radiant flux power

$$\eta_e = \Phi_e / P \,. \text{ (W/W)}$$

Luminous efficiency: is measure of light source ability to convert the consumed power P into actuation of the vision

$$\eta_\upsilon = \Phi_\upsilon / P \equiv \eta_e \times K \text{ (lm/W)}$$

where K is luminous efficacy: measure of radiation ability of the to produce visual sensation is which is measured in lm/W

$$K = \Phi_\upsilon / \Phi_e \text{ (lm/W)}$$

LED Performance
Wall Plug Efficiency

$$\eta_e = \Phi_e / P$$ Radiant efficiency $$\eta_e = \eta_{ext} \eta_f$$

$$\eta_{ext} = \eta_{inj} \times \eta_{rad} \times \eta_{opt}$$ External efficiency

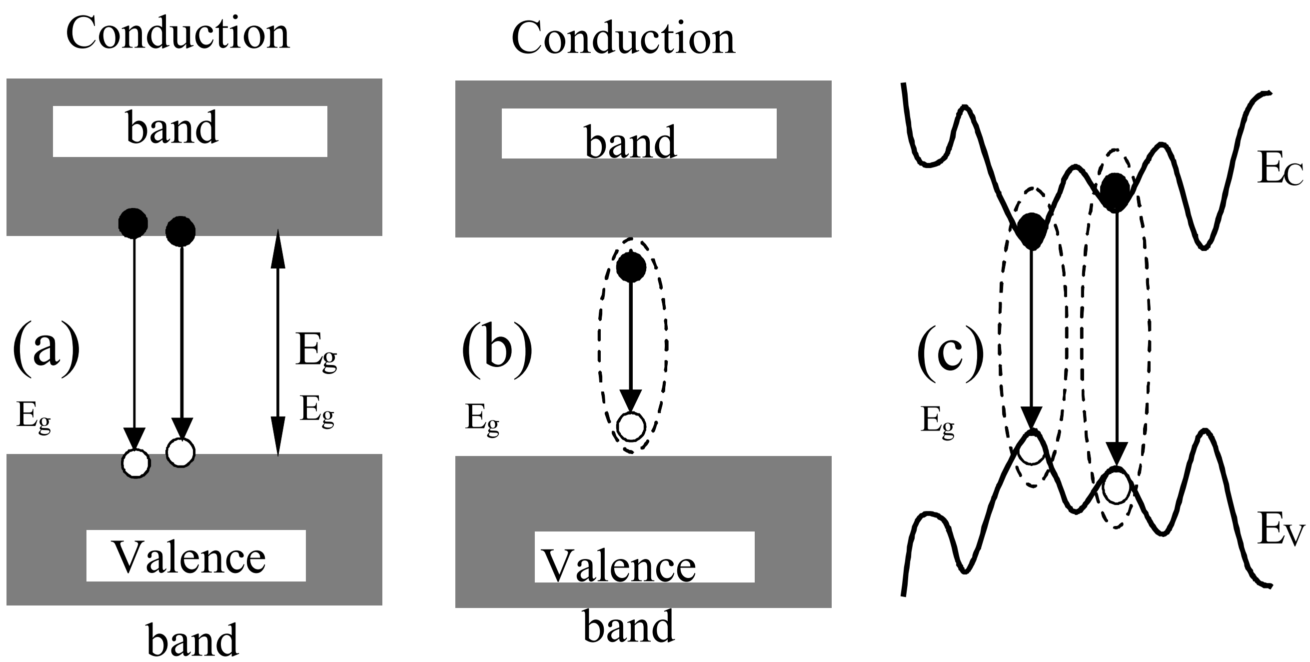
η_{rad} is internal quantum efficiency (radiative efficiency),

η_{opt} is optical efficiency (light extraction efficiency),

η_{inj} is injection efficiency,

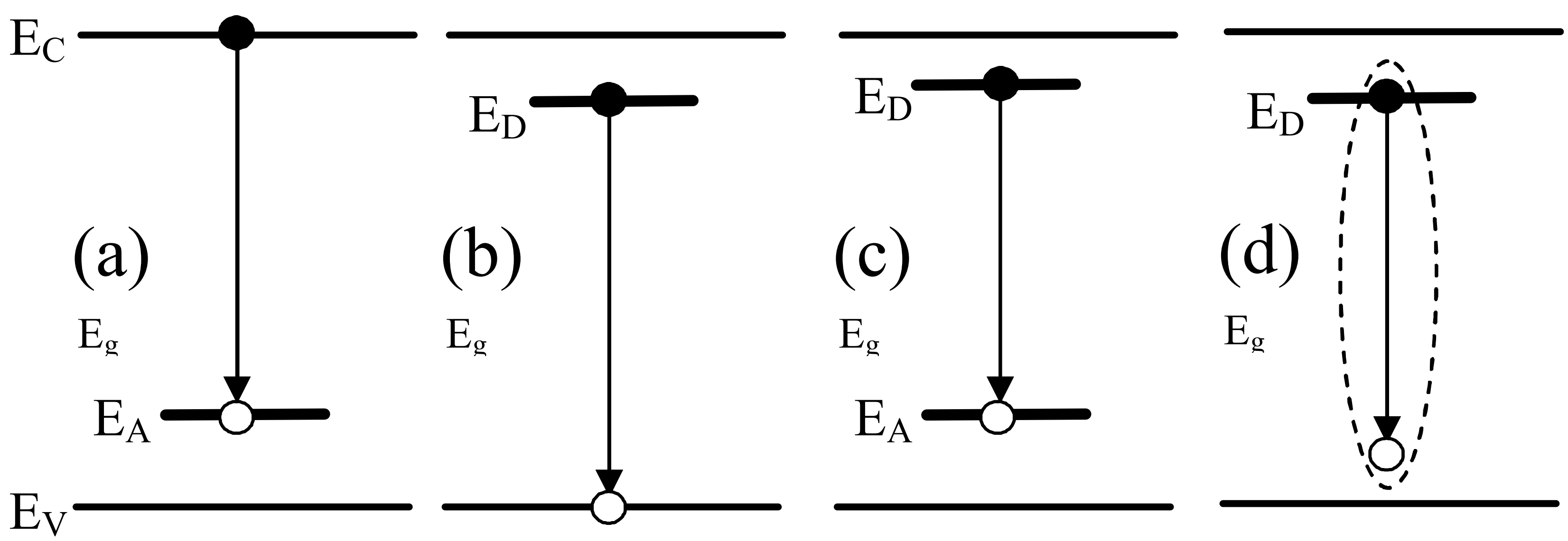
$$\eta_f = \frac{h\bar{\nu}}{qV}$$ (might be larger than unity!)

Recombination of Electrons and Holes

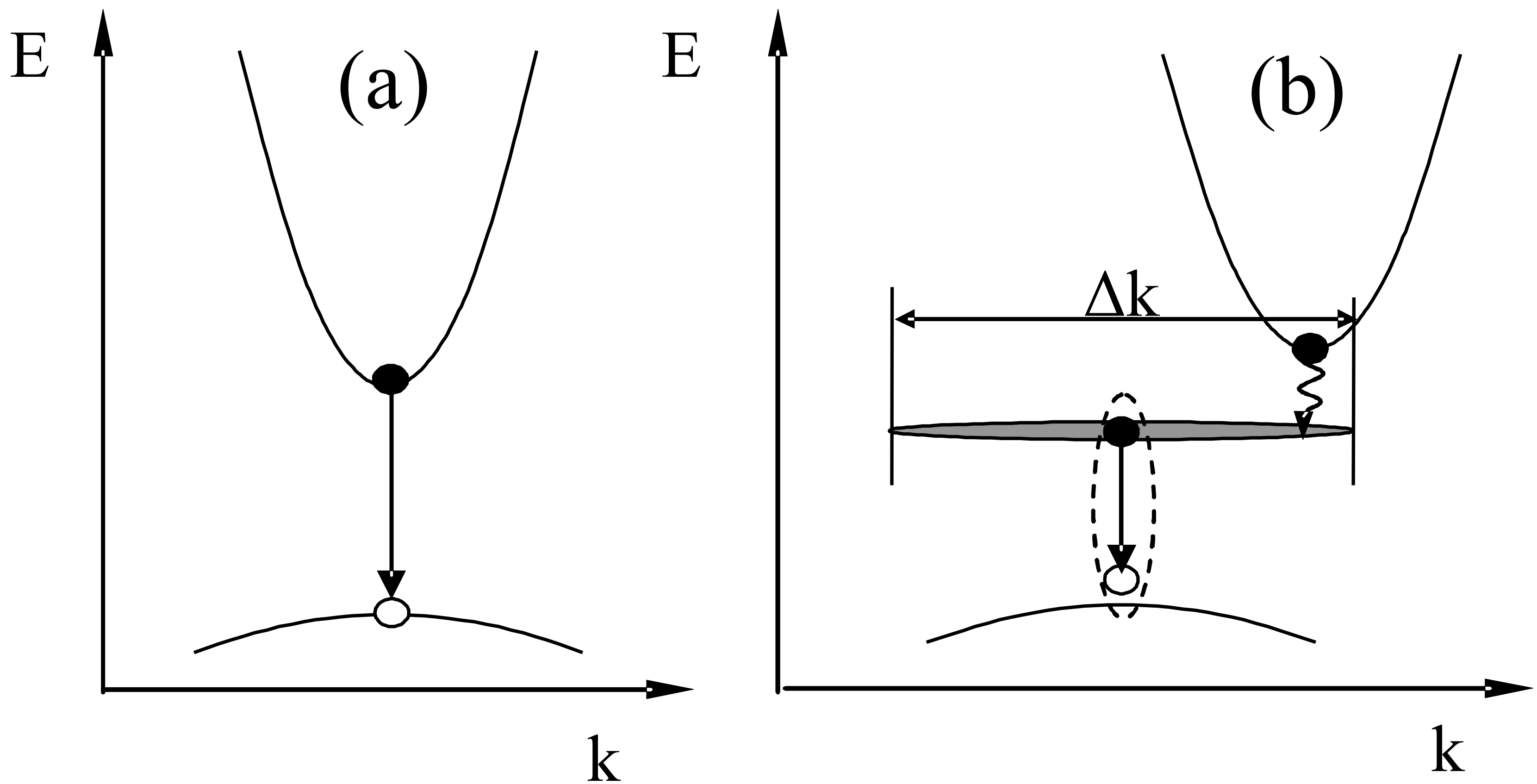


Intrinsic radiative transitions in semiconductors. (a) Band-to-band transitions; (b) free-exciton annihilation; (c) recombination of exciton localized at band-potential fluctuations

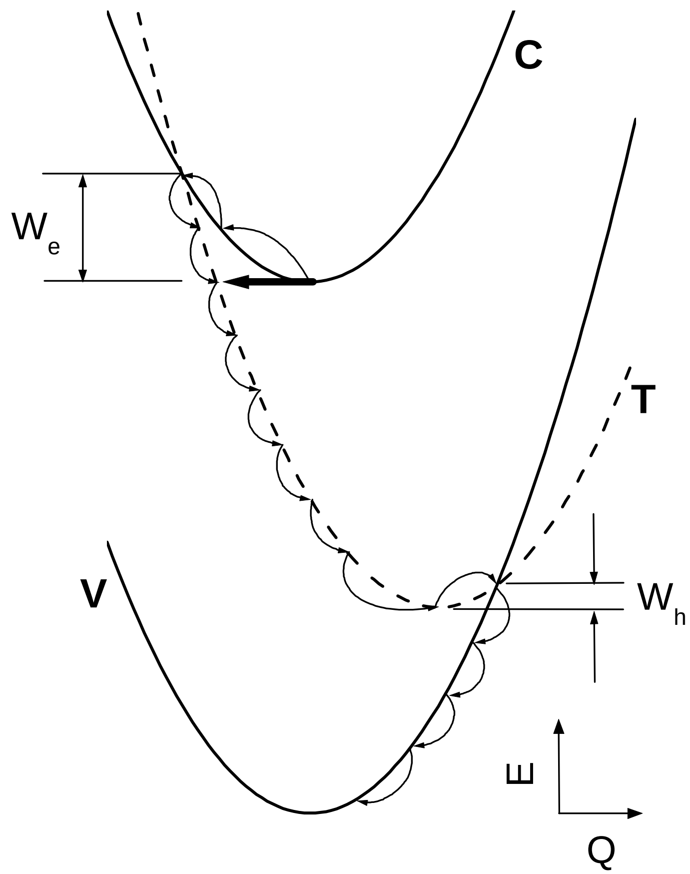
Radiative recombination involving impurity levels. (a) Donor-state–valence-band transition; (b) conduction-band–acceptor-state transition; (c) donor-acceptor recombination; (d) bound-exciton recombination



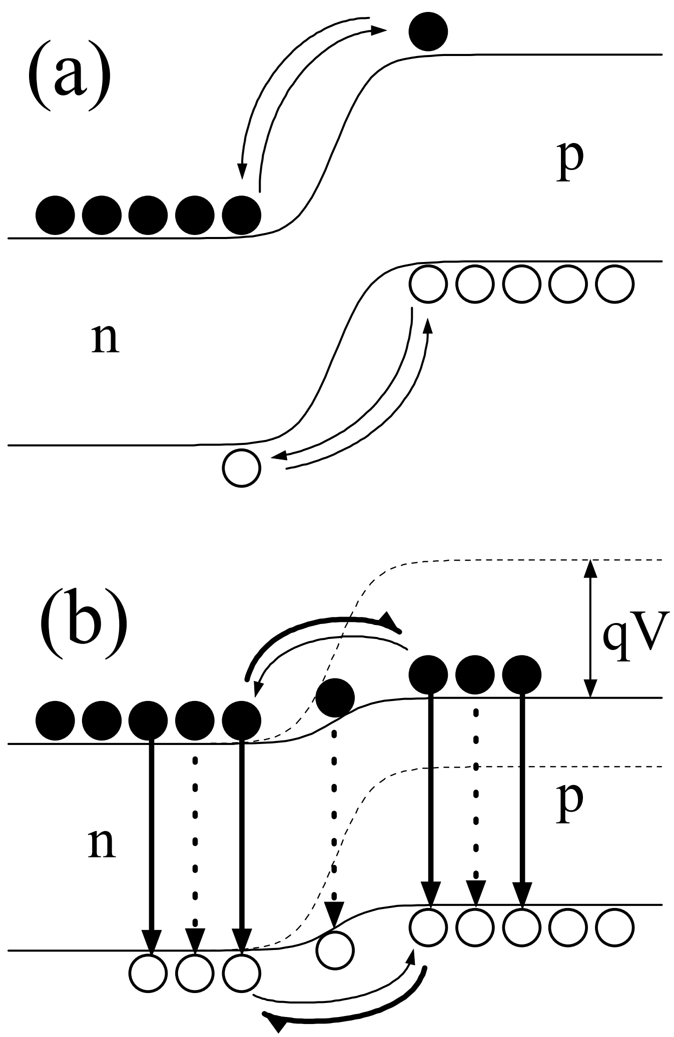
(a) Vertical band-to-band radiative transition in direct gap semiconductor; (b) impurity assisted radiative transition in indirect gap semiconductor.



Configuration co-ordinate diagram of a deep centre of nonradiative recombination. Potential curves C, T, and V correspond to the electron in the conduction band, at the trap, and in the valence band, respectively.

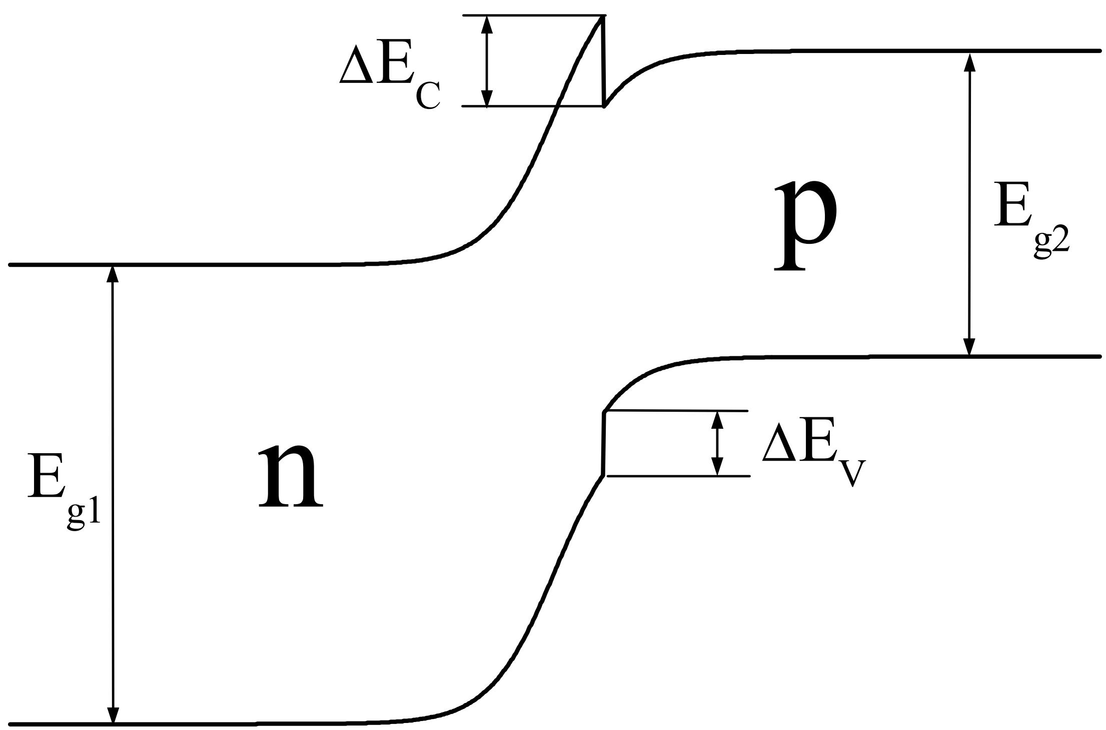


Injection in a *p-n* junction LED

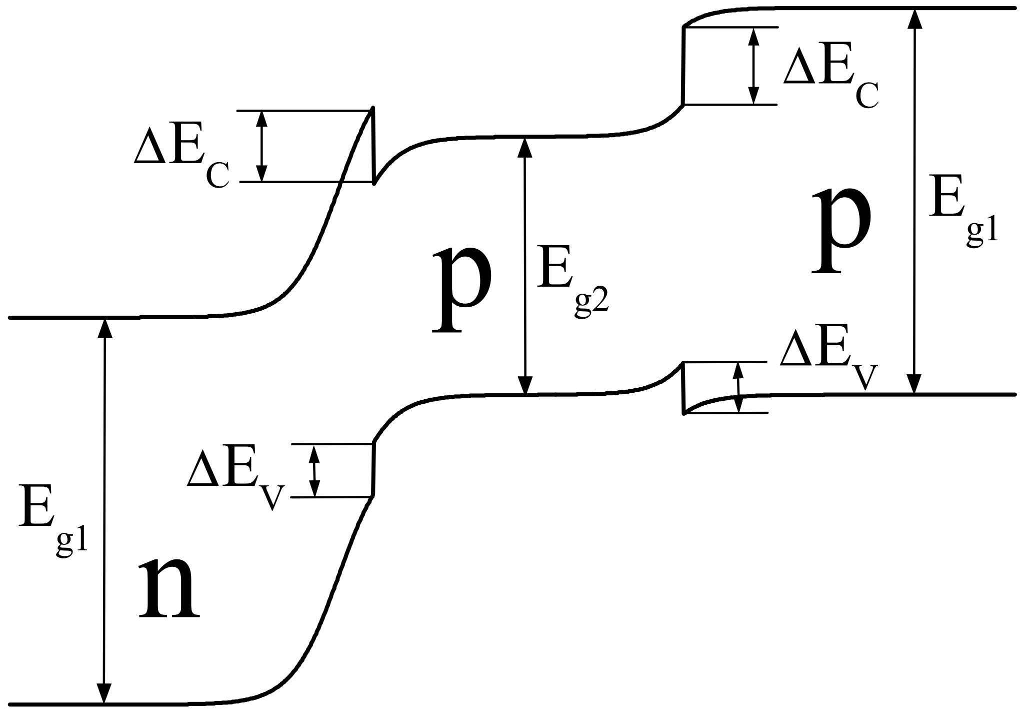


(a) Zero bias
(b) Forward bias

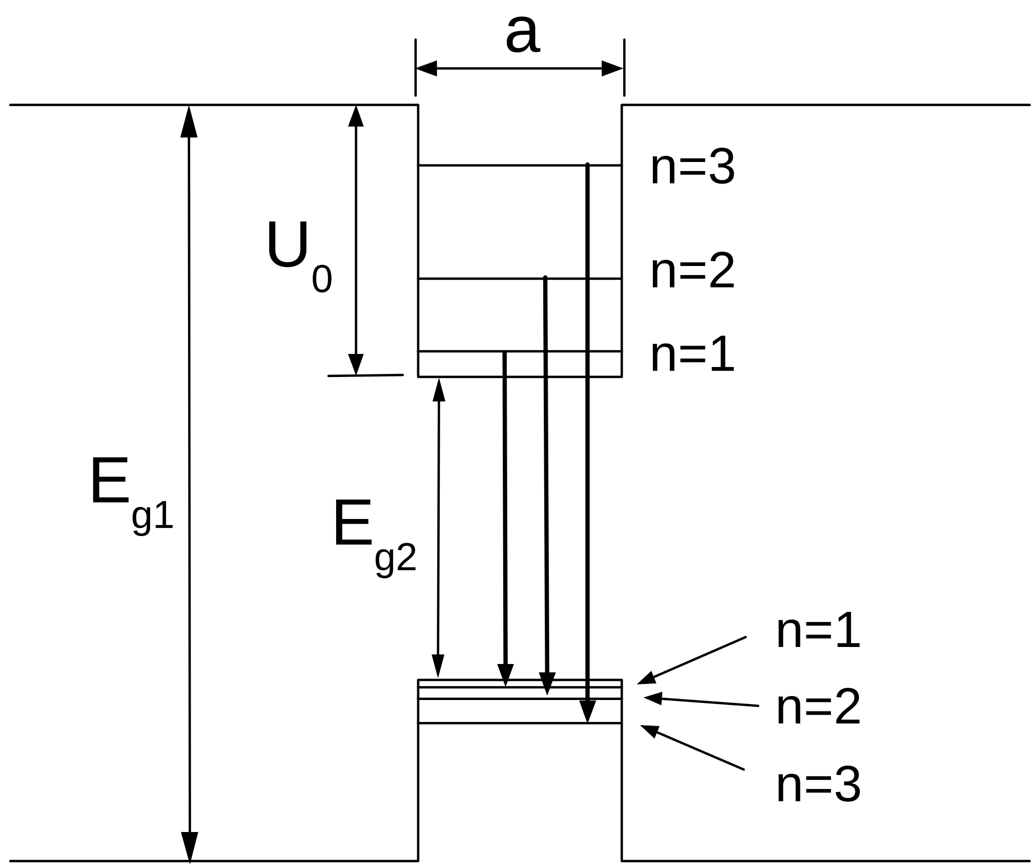
Heterostructures and Quantum Wells



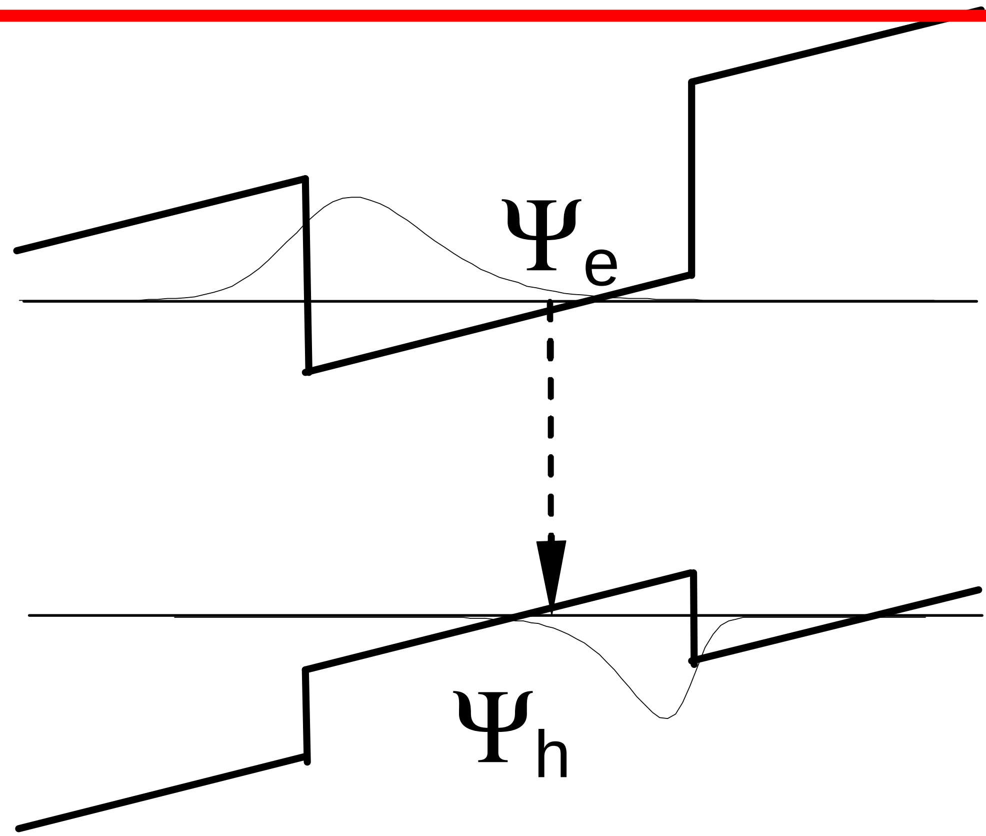
Double Heterostructure LED



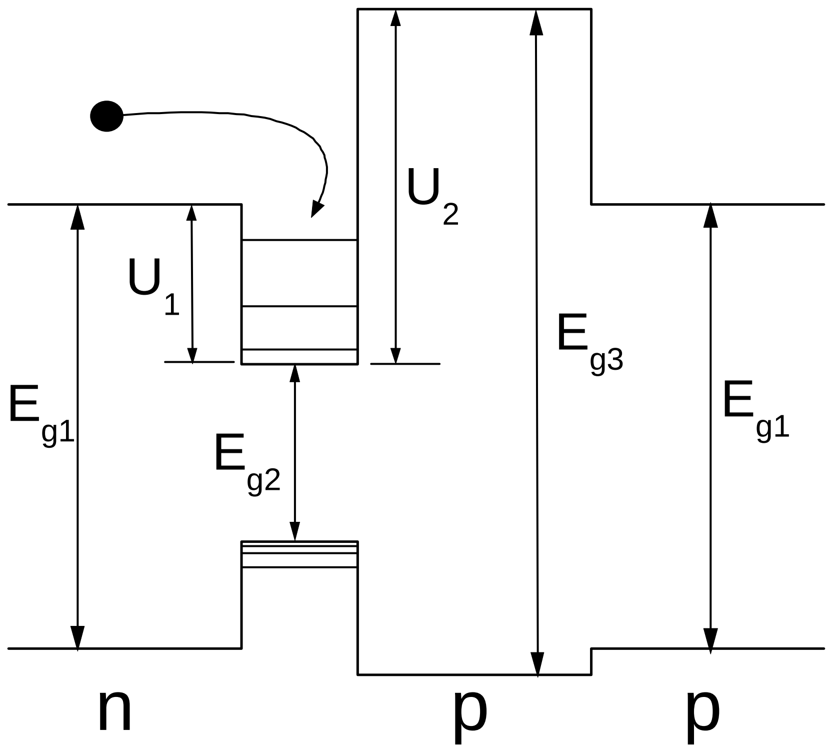
Band Alignment and Quantum Well Transitions



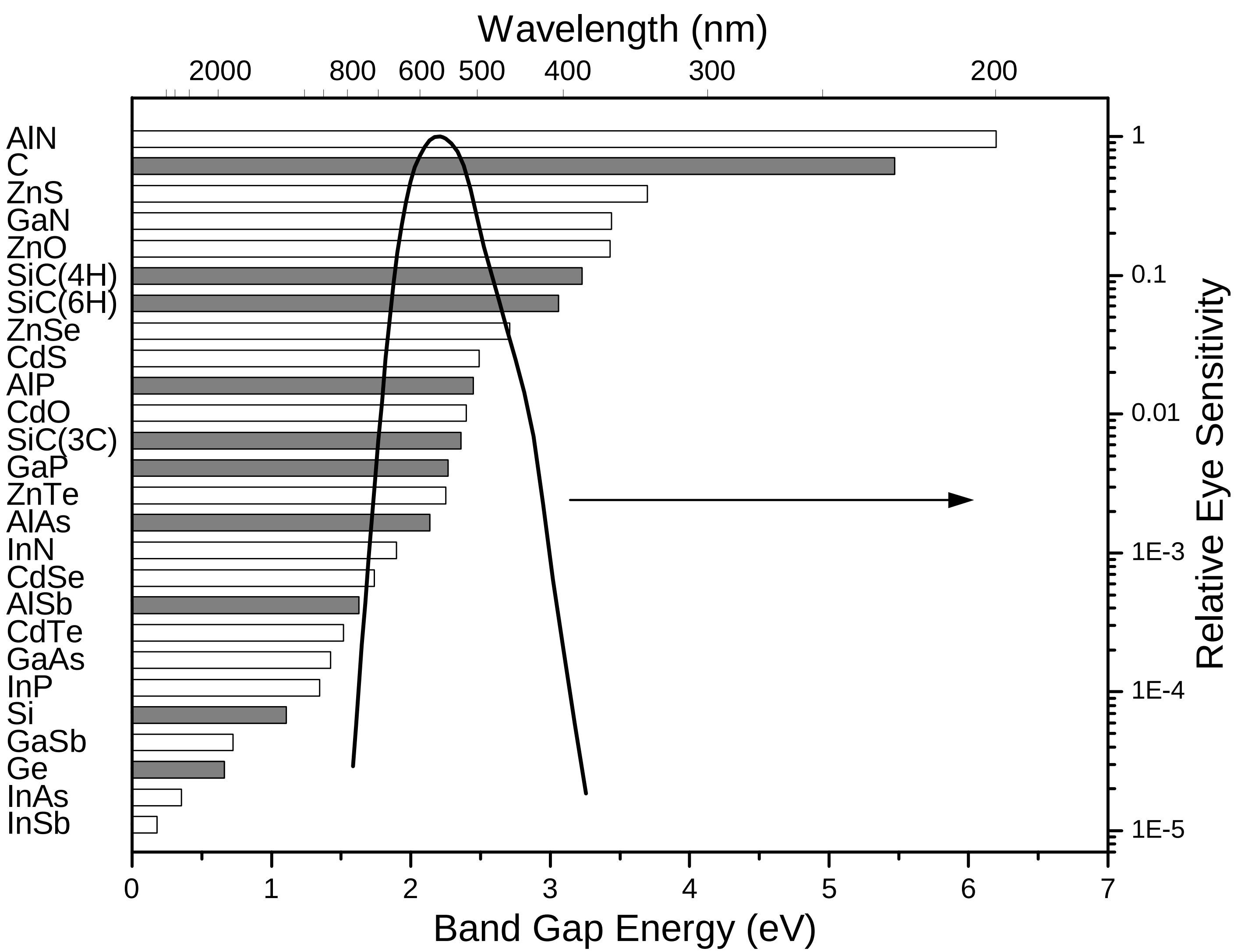
Effect of the Built-in Field



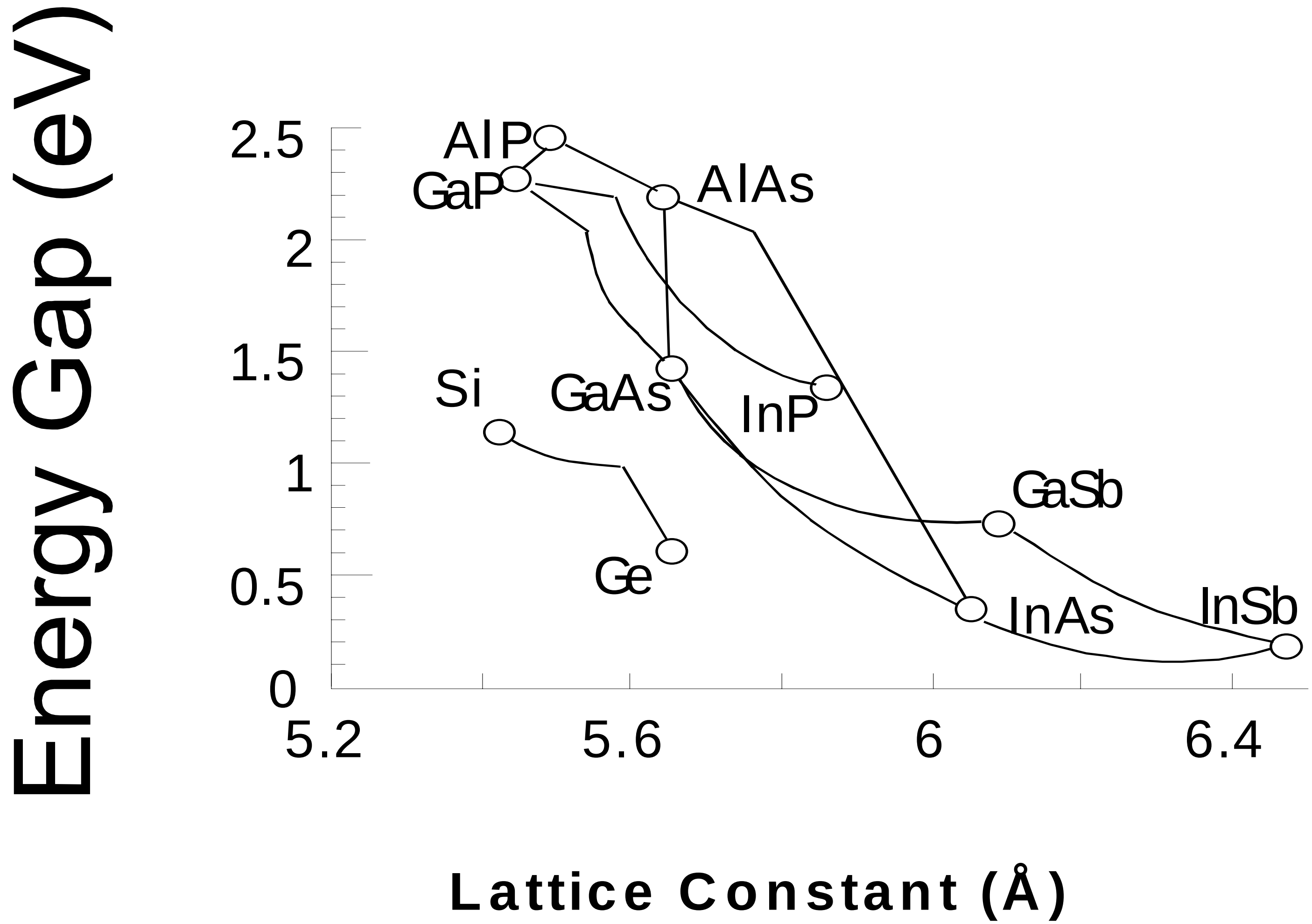
Electron Blocking Layer



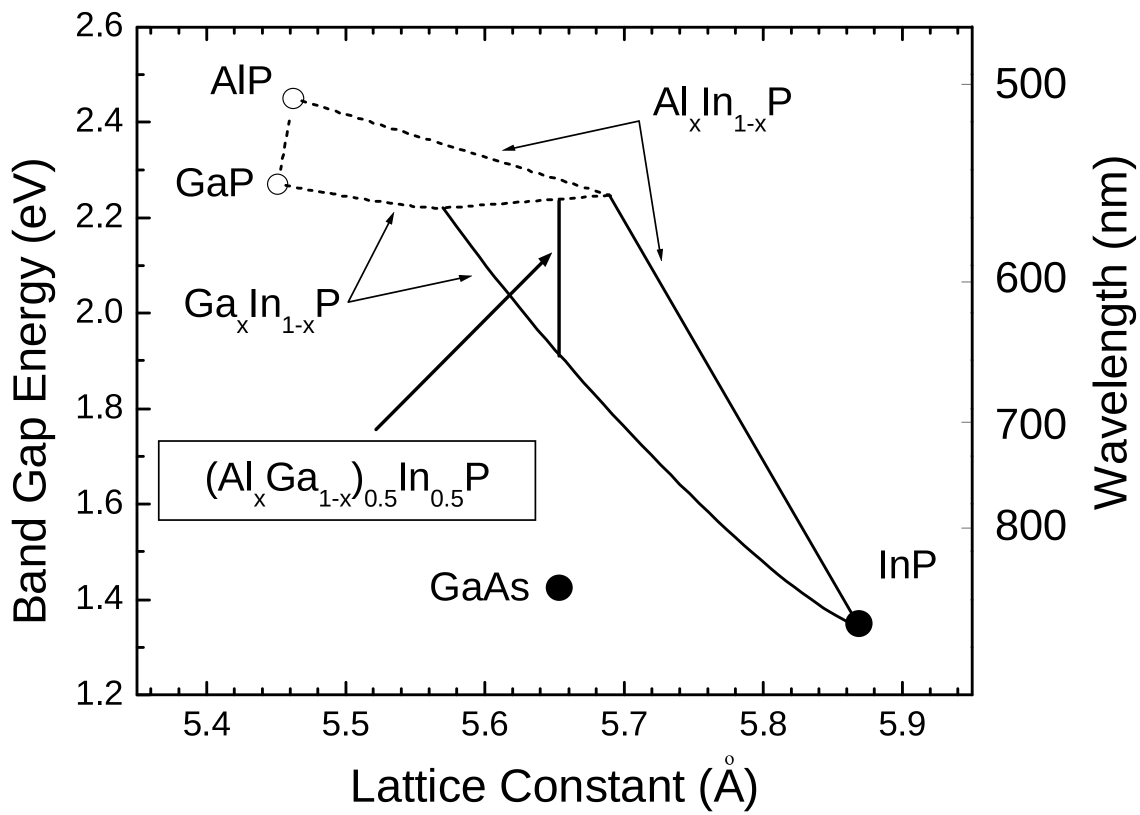
SEMICONDUCTOR MATERIALS SYSTEMS FOR HIGH BRIGHTNESS LEDs



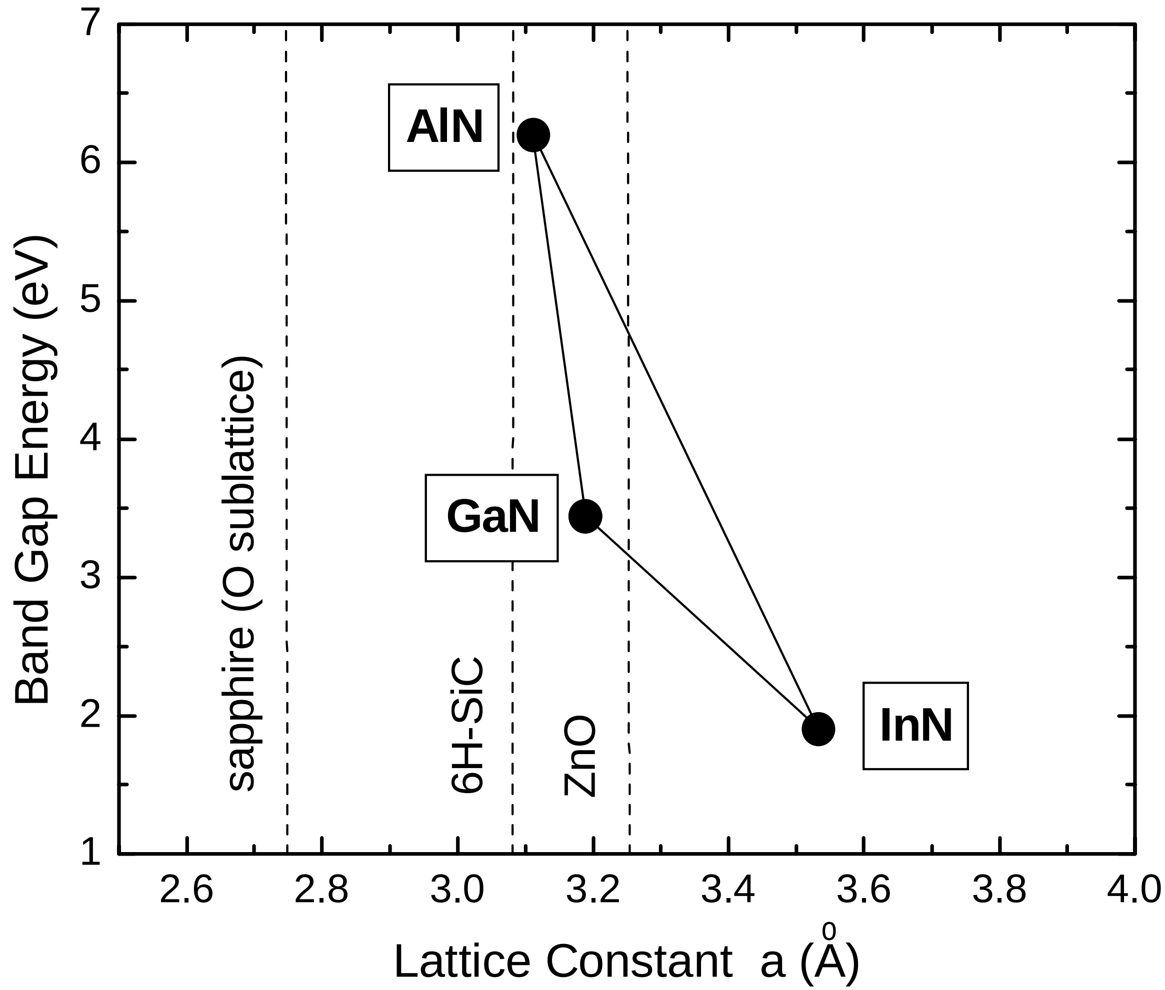
AlGaAs Materials System



AlGaInP Materials System



AlInGaN Materials System

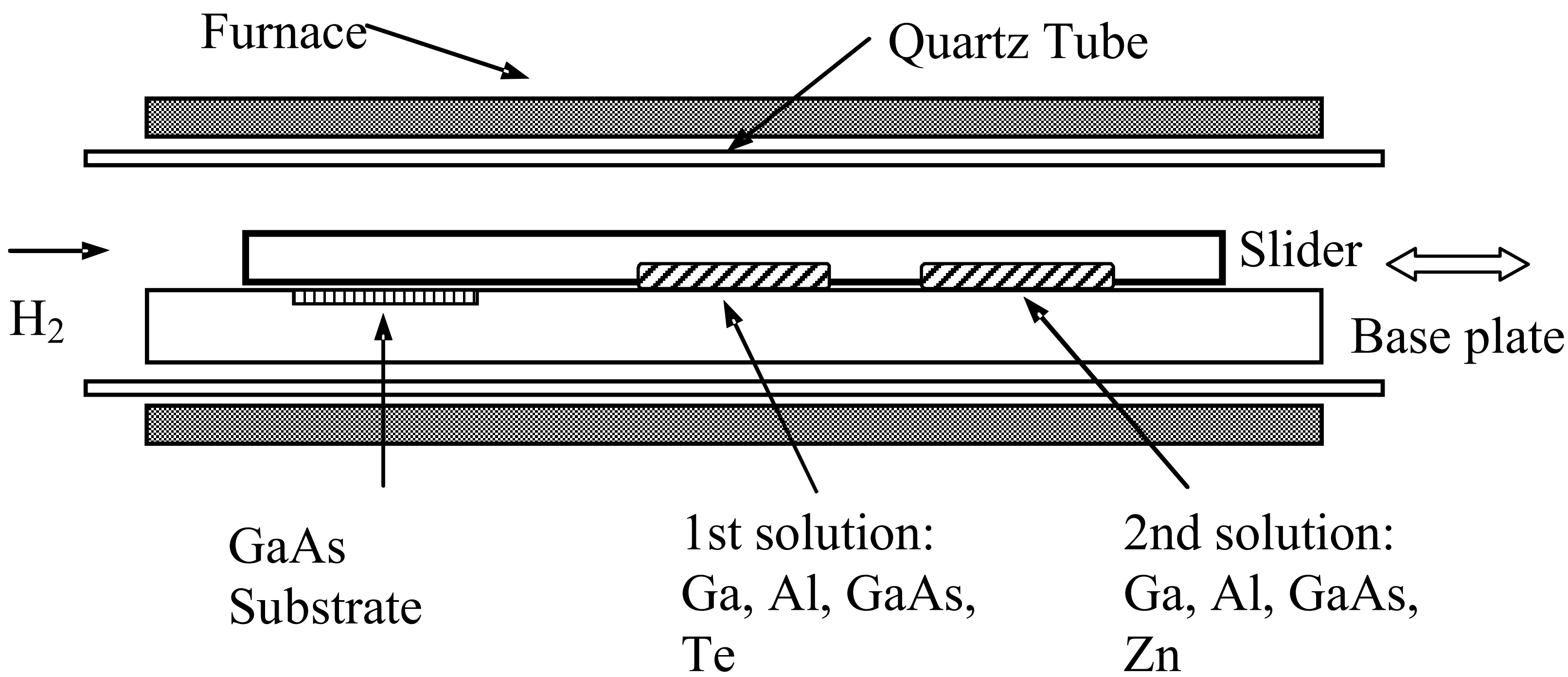


M. E. Levinshtein, S. L. Rumyantsev, and M. S. Shur, Editors, “Properties of Advanced Semiconductor Materials: GaN, AlN, InN, BN, and SiGe“, John Wiley and Sons, ISBN 0-471-35827-4, New York (2001)

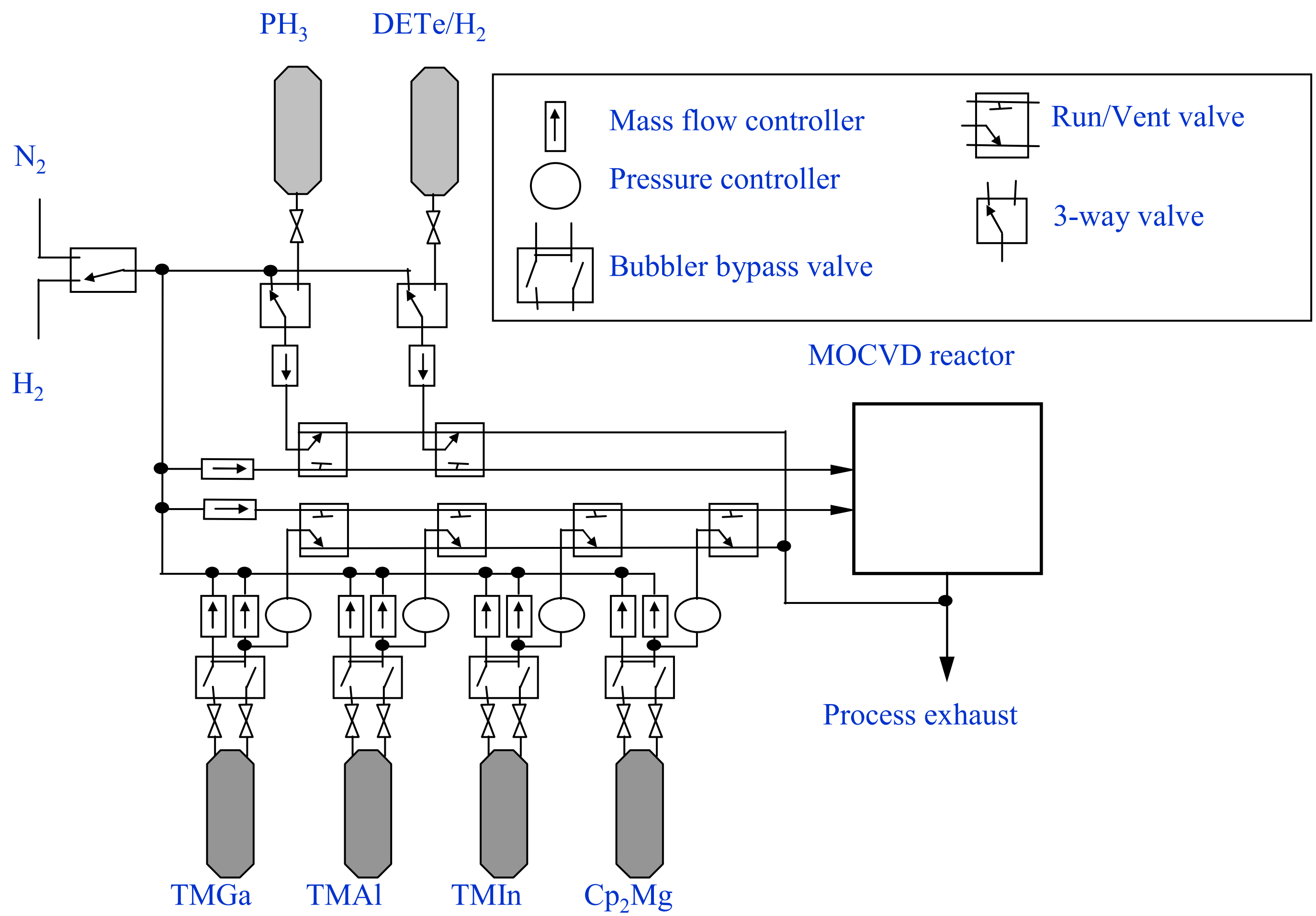
Basic parameters of InN, GaN, and AlN at 300 K

Parameter	Units	GaN	AlN	InN
Lattice constant, c	Å	5.186	4.982	5.693
Lattice constant, a	Å	3.189	3.112	3.533
Band gap energy, E_g	eV	3.339[a]	6.2	1.97
Effective electron mass, m_e	m_0	0.19[b] (‖) 0.17[b] (⊥)	0.33[c] (‖) 0.25[c] (⊥)	0.11[b] (‖) 0.10[b] (⊥)
Effective heavy hole mass, m_{hh}	m_0	1.76[c] (‖) 1.61[c] (⊥)	3.53[c] (‖) 10.42[c] (⊥)	1.56[b] (‖) 1.68[b] (⊥)
Effective light hole mass, m_{lh}	m_0	1.76[c] (‖) 0.14[c] (⊥)	3.53[c] (‖) 0.24[c] (⊥)	1.56[b] (‖) 0.11[b] (⊥)
Piezoelectric constant, e_{31}	C/m^2	-0.33	-0.48	-0.57
Piezoelectric constant, e_{33}	C/m^2	0.65	1.55	0.97
Spontaneous polarization, $P_{\parallel}$[d]	C/m^2	-0.029	-0.081	-0.032
Radiative recombination coefficient[e]	cm^3/s	4.7×10^{-11}	1.8×10^{-11}	5.2×10^{-11}
Refraction index at 555 nm		2.4	2.1	2.8
Absorption coefficient at the photon energy $h\nu \approx E_g$	10^5 cm^{-1}	1	3	0.4

Materials Growth Techniques. LPE

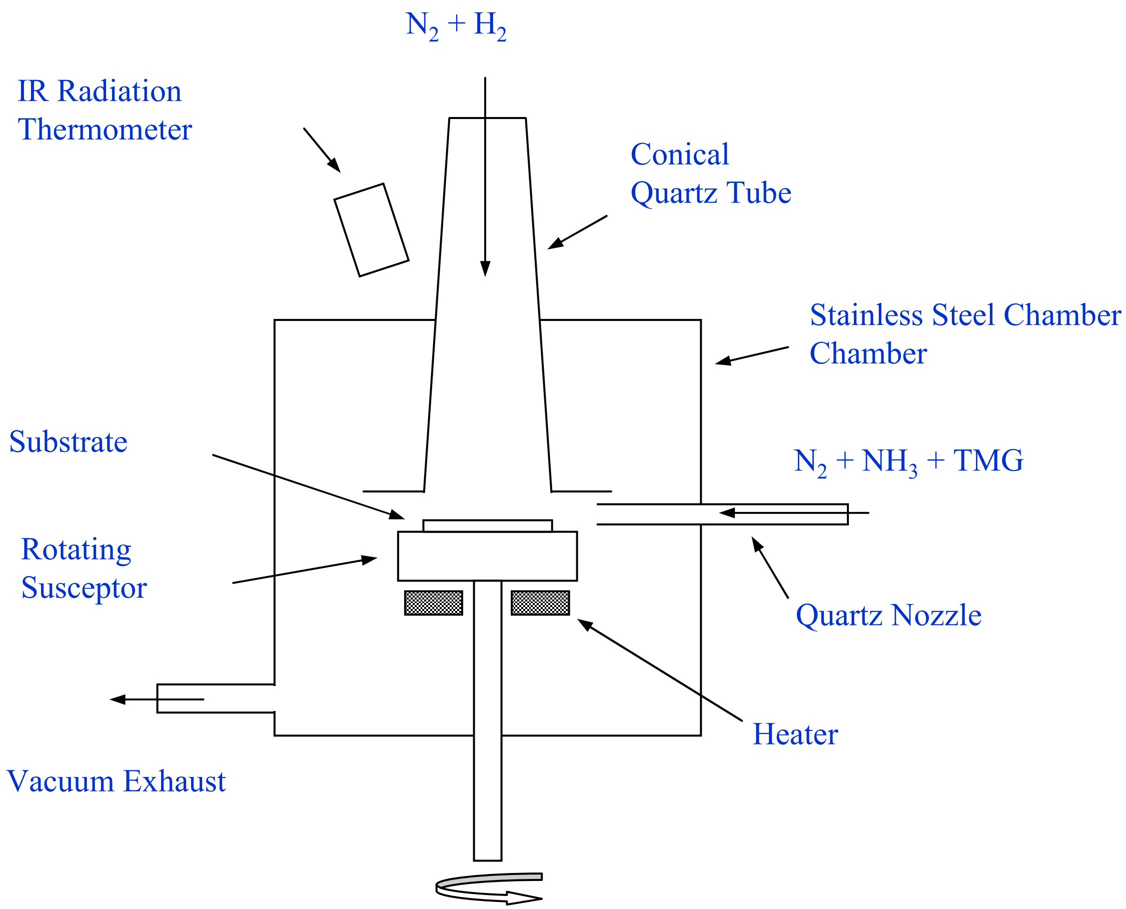


MOCVD



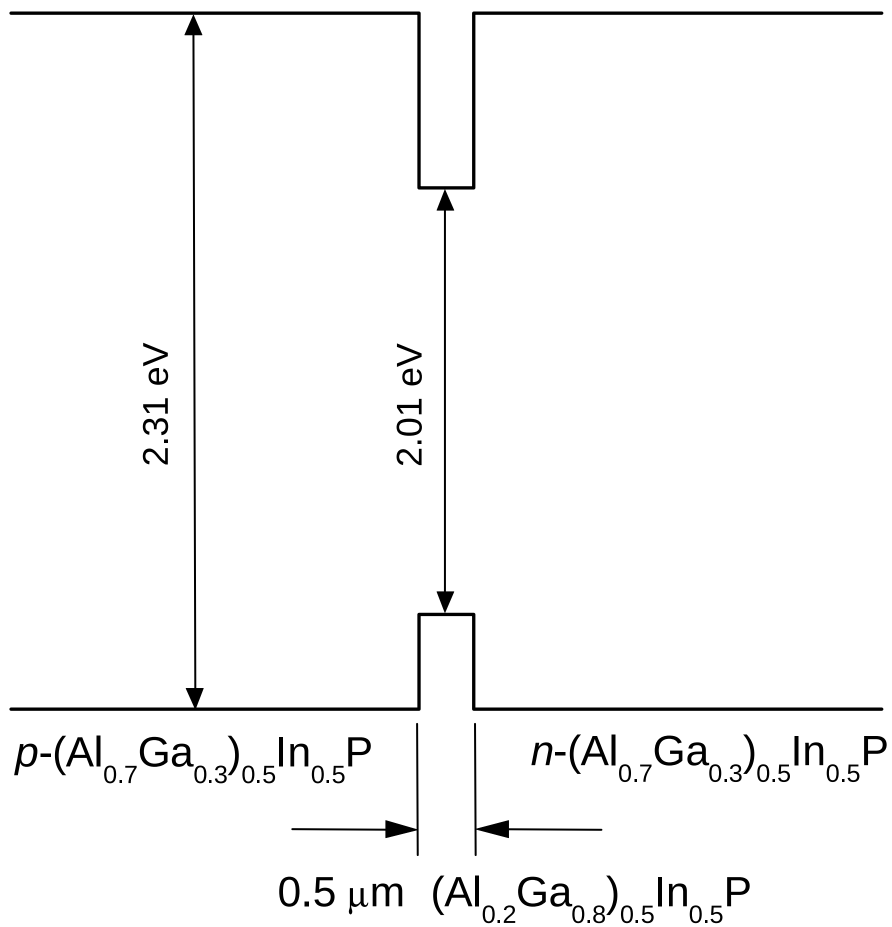
PH3
DETe/H2
N2
H2
Mass flow controller
Pressure controller
Bubbler bypass valve
Run/Vent valve
3-way valve
MOCVD reactor
Process exhaust
TMGa
TMAl
TMIn
Cp2Mg

MOCVD (continued)



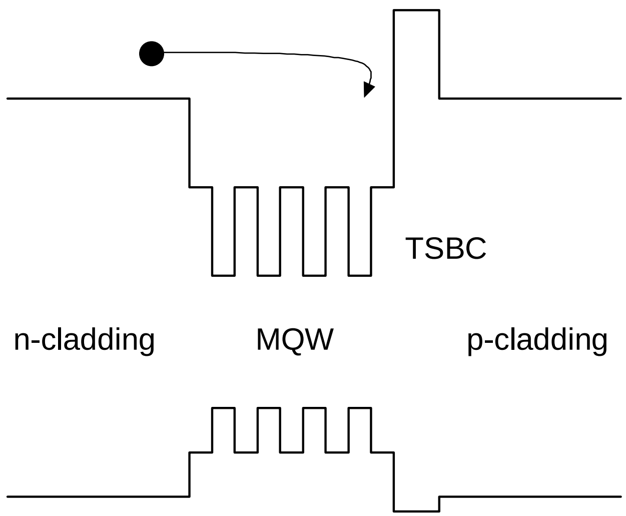
After S.Nakamura, *Jpn. J. Appl. Phys.* **30**, L1705, 1991.

ELECTROLUMINESCENCE IN HIGH BRIGHTNESS LEDs

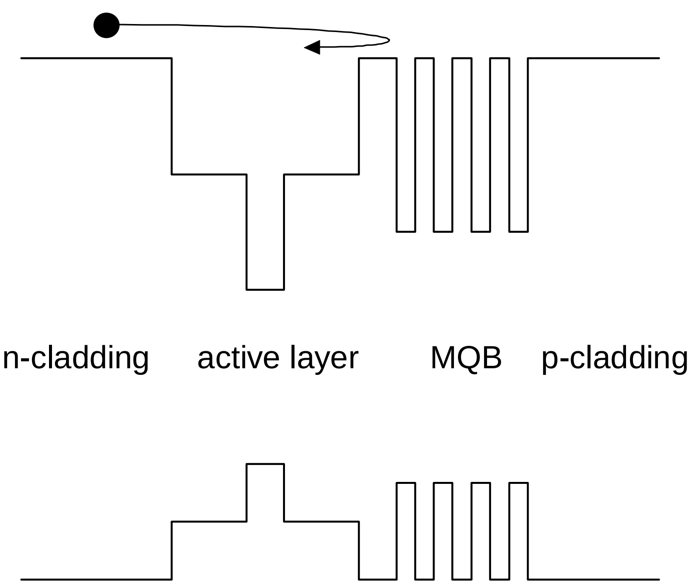


Schematic of the band gap alignment in advanced AlGaInP LEDs. (a) Structure with tensile strain barrier cladding (electron blocking) layer (after S.J.Chang *et al.*, *IEEE Photonic Tech. L.* **9**, 1199, 1997); (b) structure with a multiquantum barrier (MQB) (after C.S.Chang *et al.*, *IEEE J. Quantum Elect.* **34**, 77, 1998).

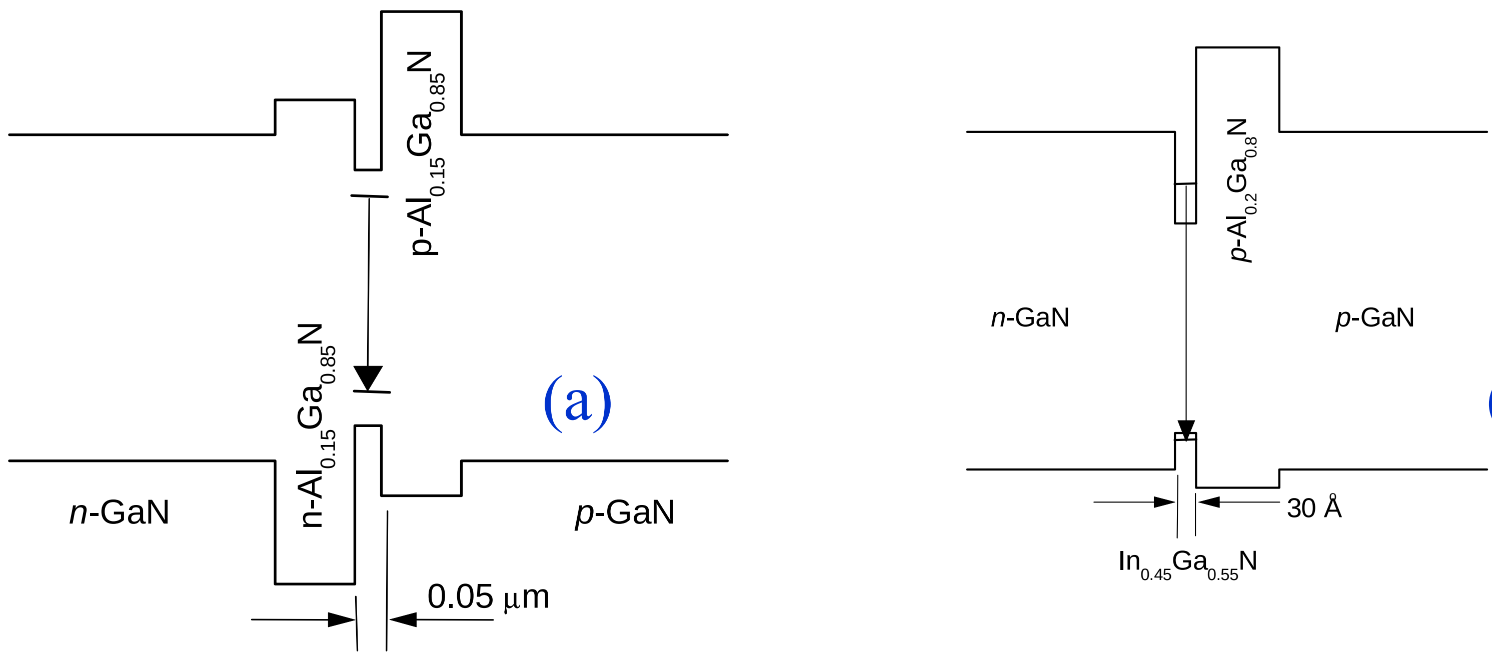
(a)



(b)

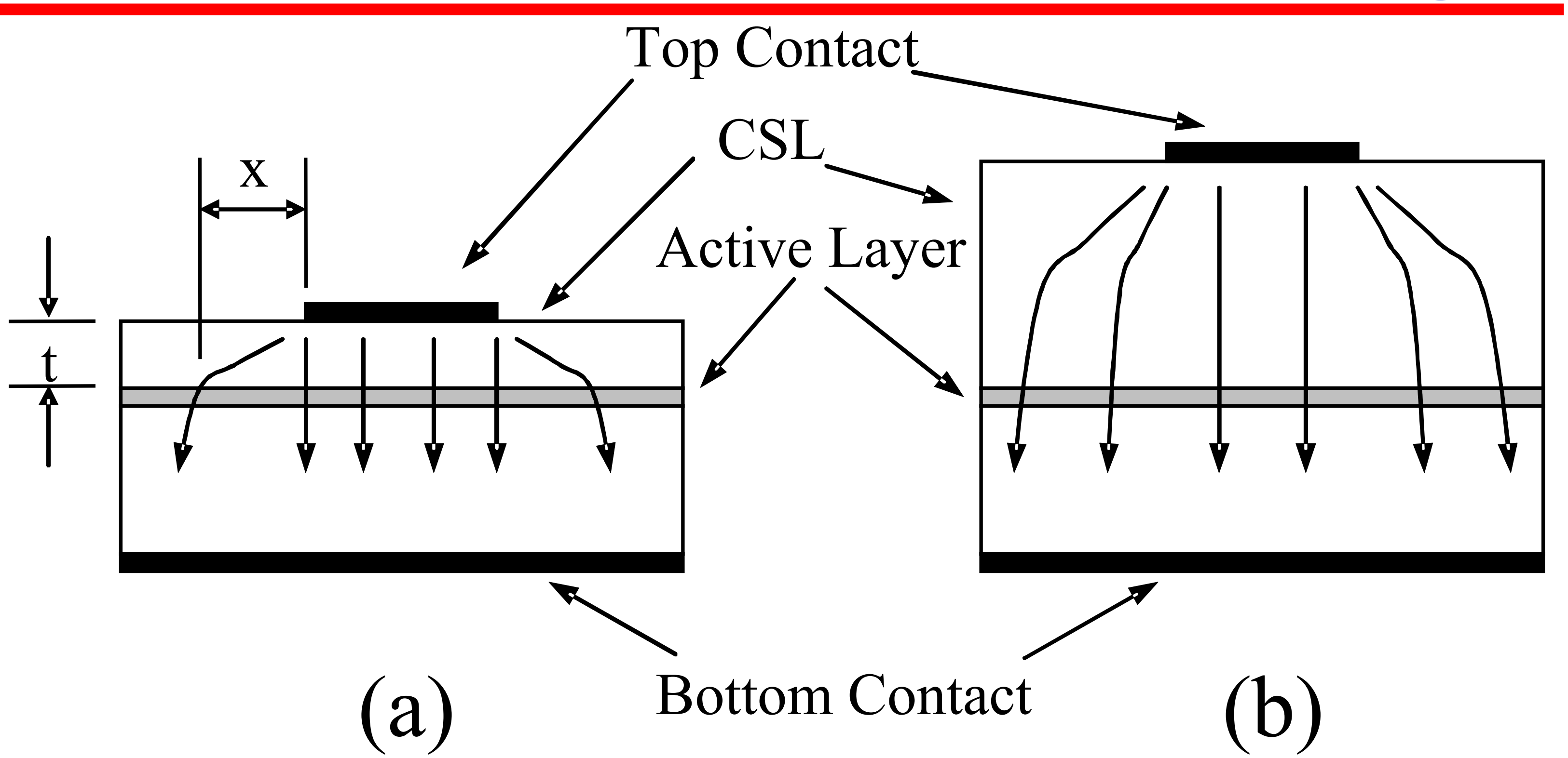


Schematic of band gap alignment in AlInGaN LEDs.



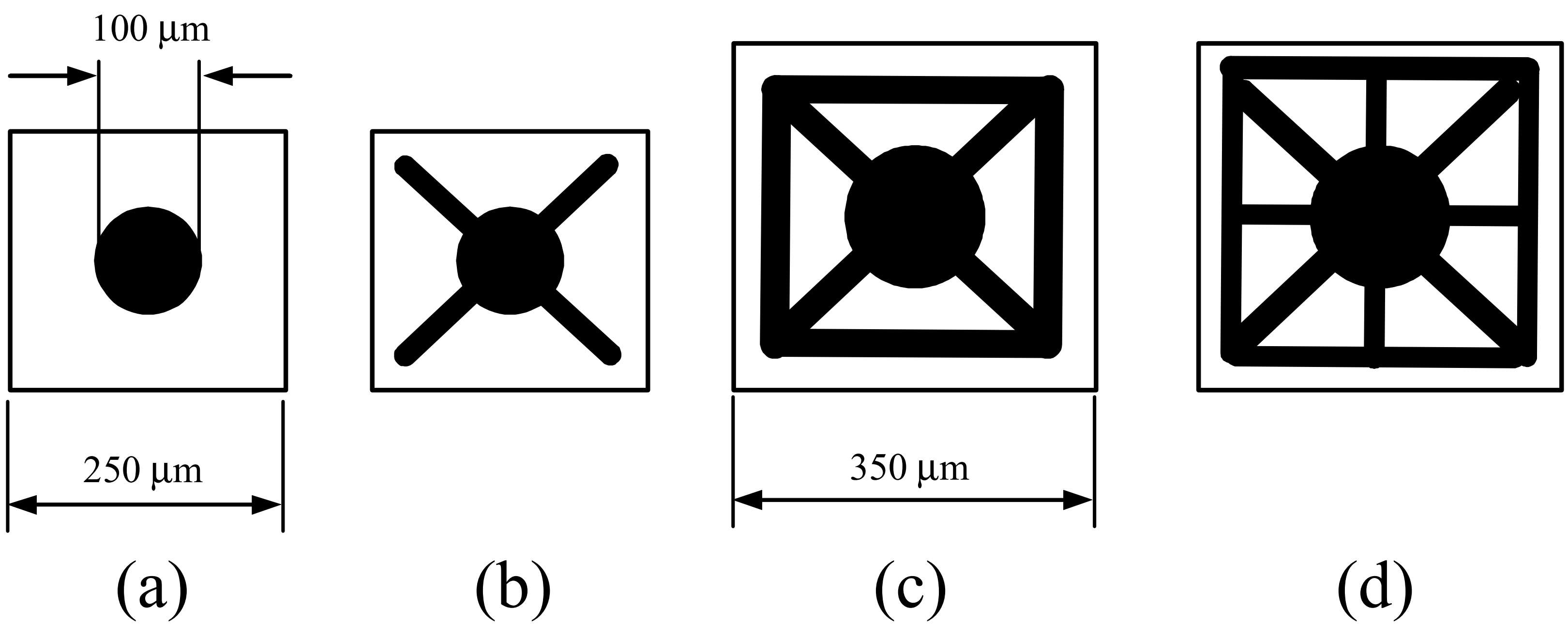
(a) DH-based structure with two wide-band-gap cladding layers; radiative transitions occur between donor-acceptor pairs (after S.Nakamura *et al., J. Appl. Phys.* **76**, 8189, 1994);
(b) SQW structure with asymmetric confining layers; radiative transitions occur between quantum-confined levels of electrons and holes (after S.Nakamura *et al., Jpn. J. Appl. Phys.* **34,** L1332, 1995)

Contacts and Current Spreading



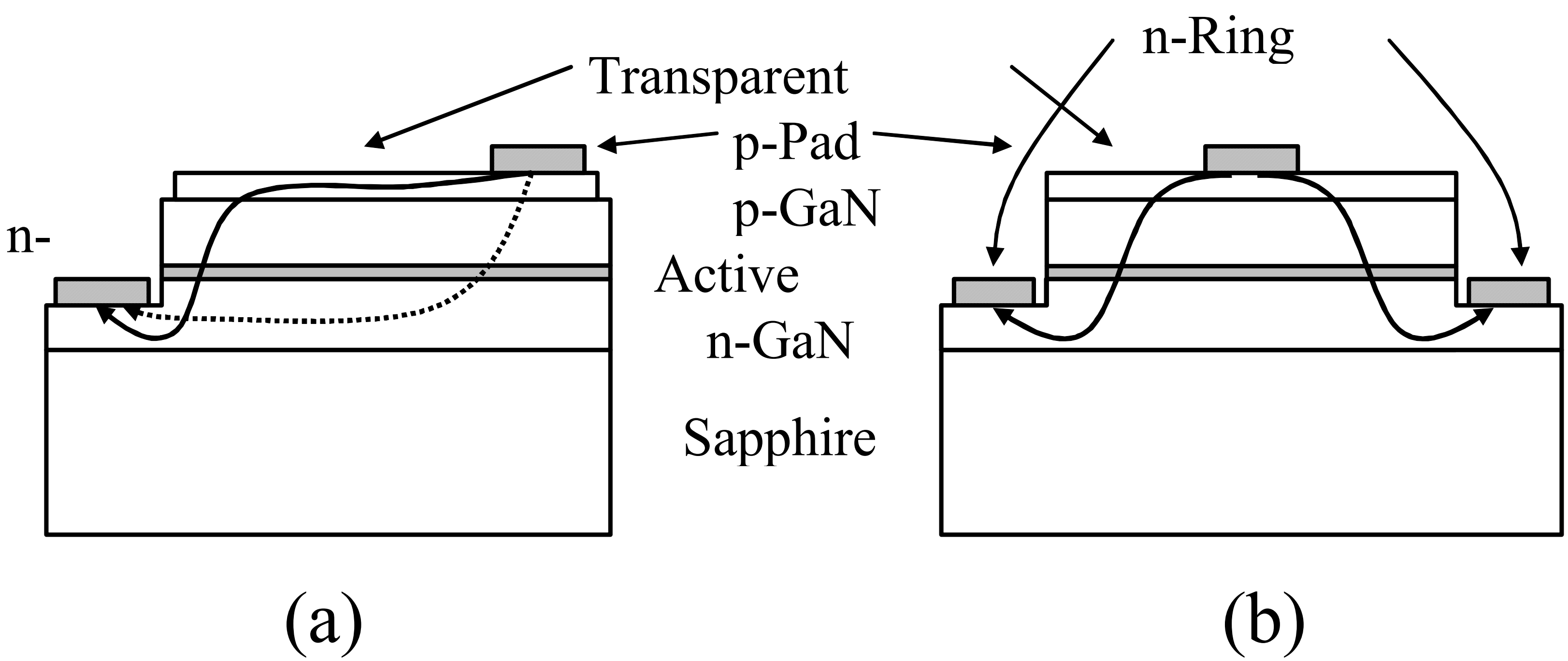
a) Thin/low-conductivity current spreading layer. The current crowds under the top contact. (b) Thick/high-conductivity CSL. The current uniformly spreads over the entire cross-section.

Contact Geometries

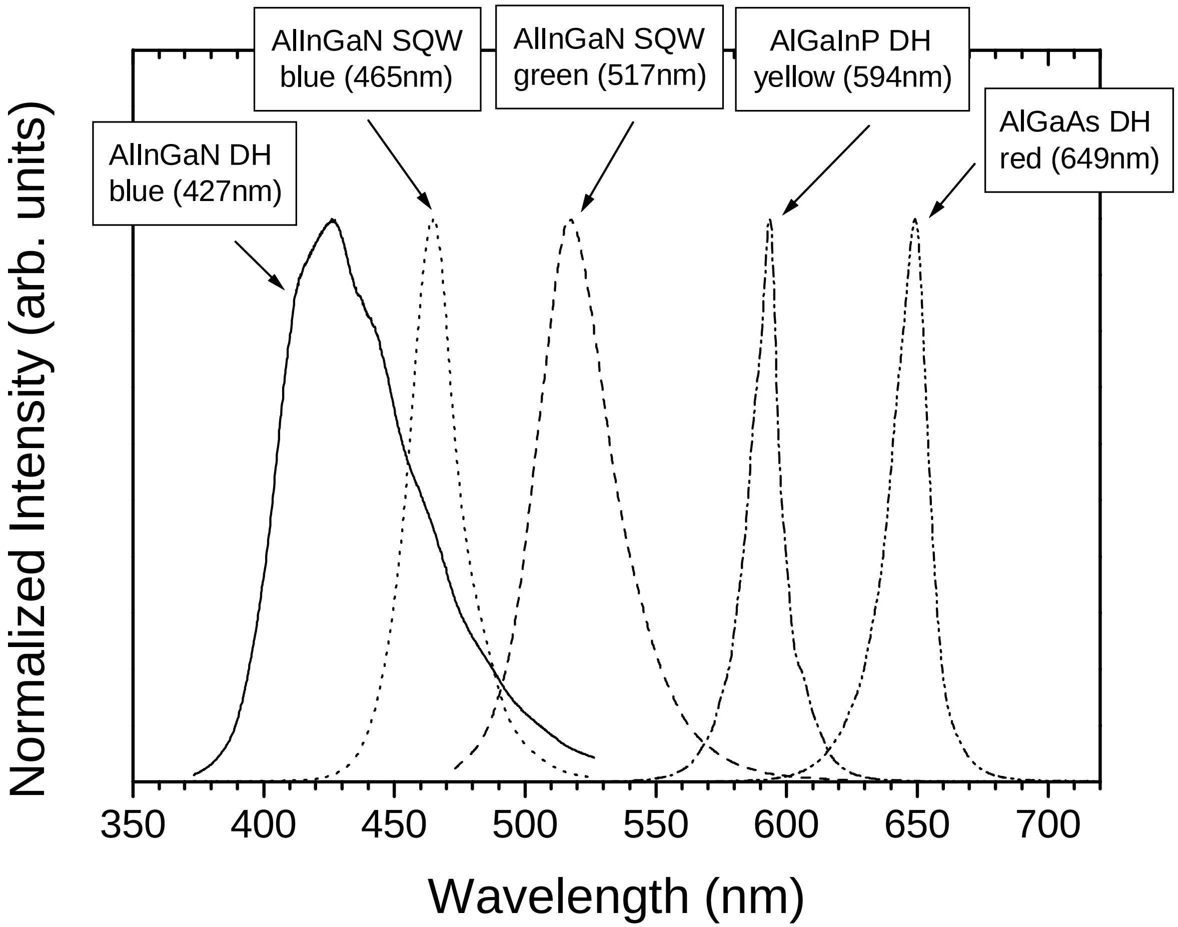


Current paths in AlInGaN chips grown on sapphire.

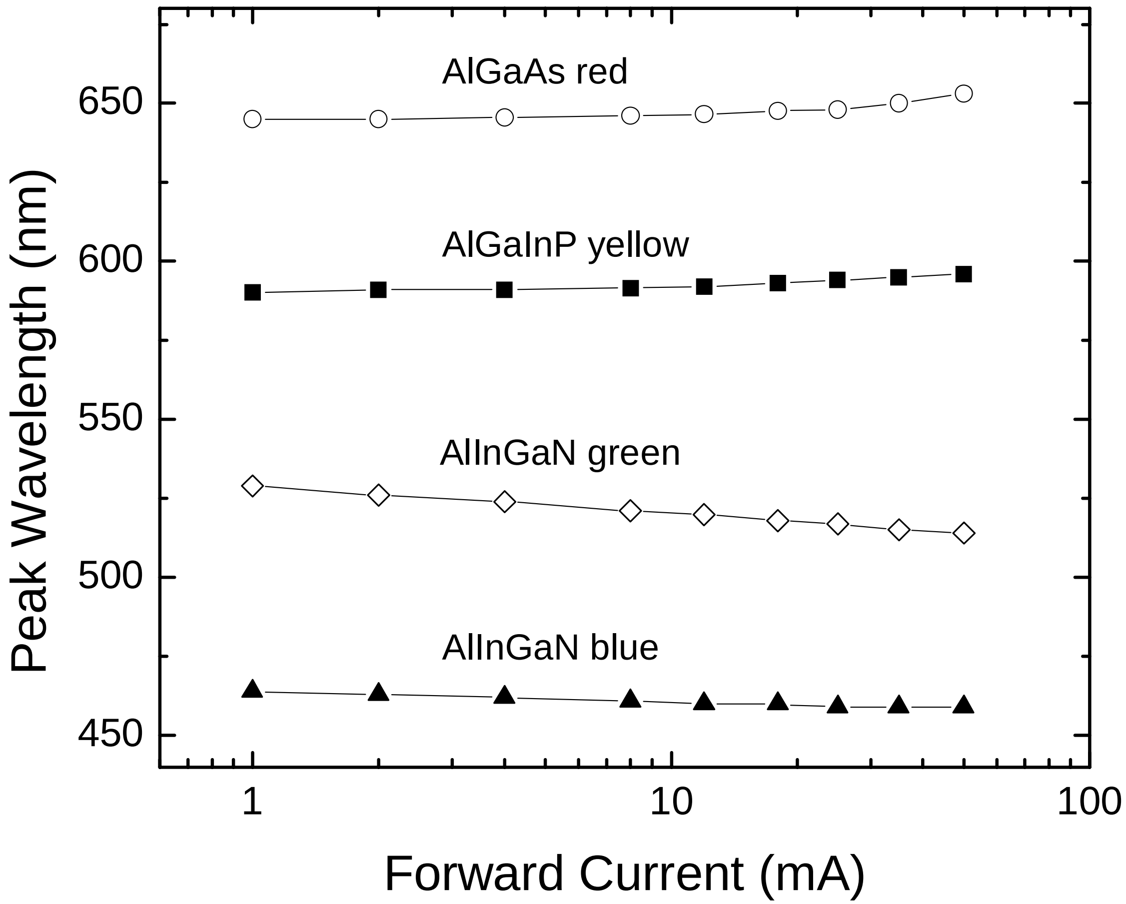
(a) asymmetric design with current crowding towards the *n*-pad; (b) symmetric design with a ring *n*-pad (after M. R. Krames *et al.*, *Proc. SPIE* **3938**, 2, 2000).



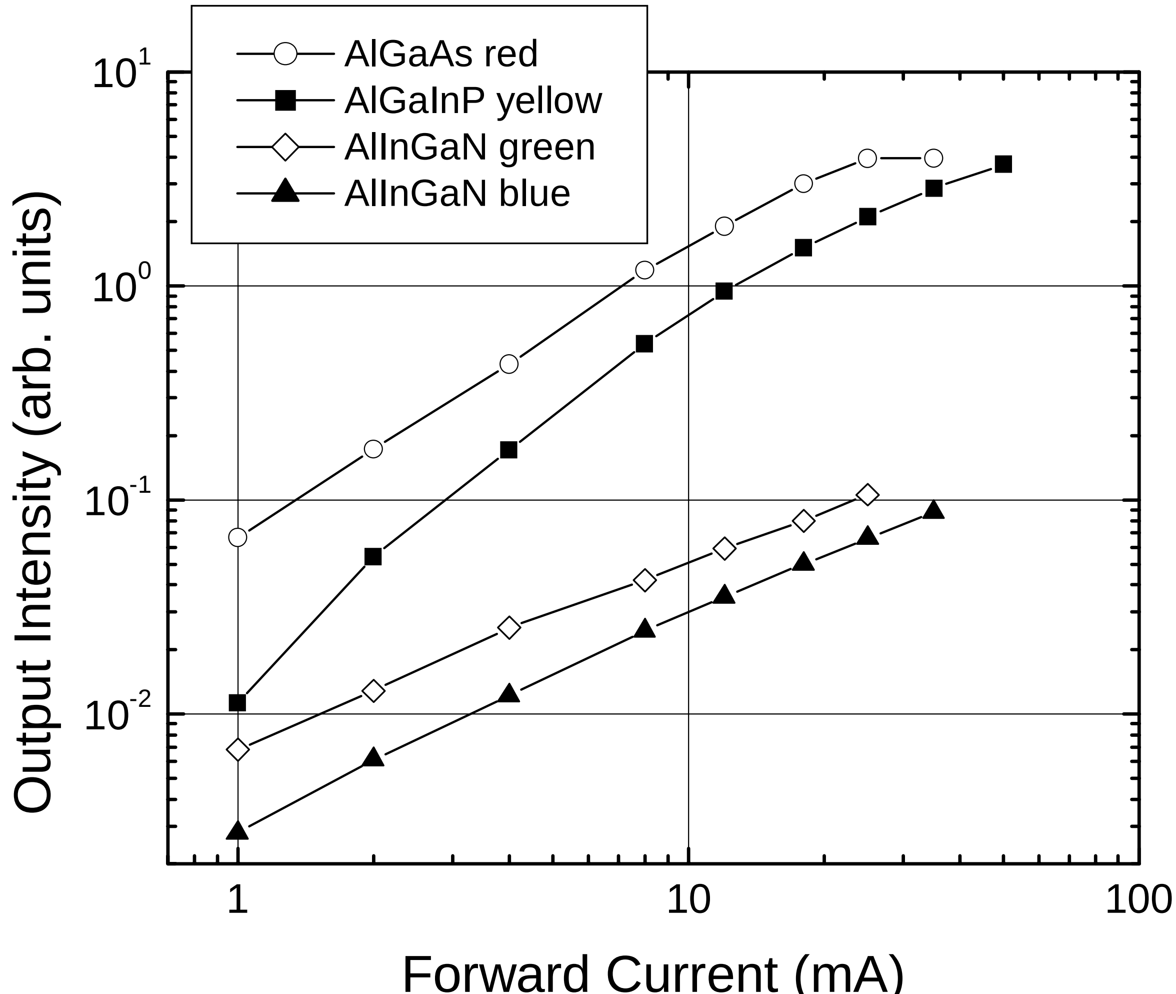
Emissive and Electrical Characteristics



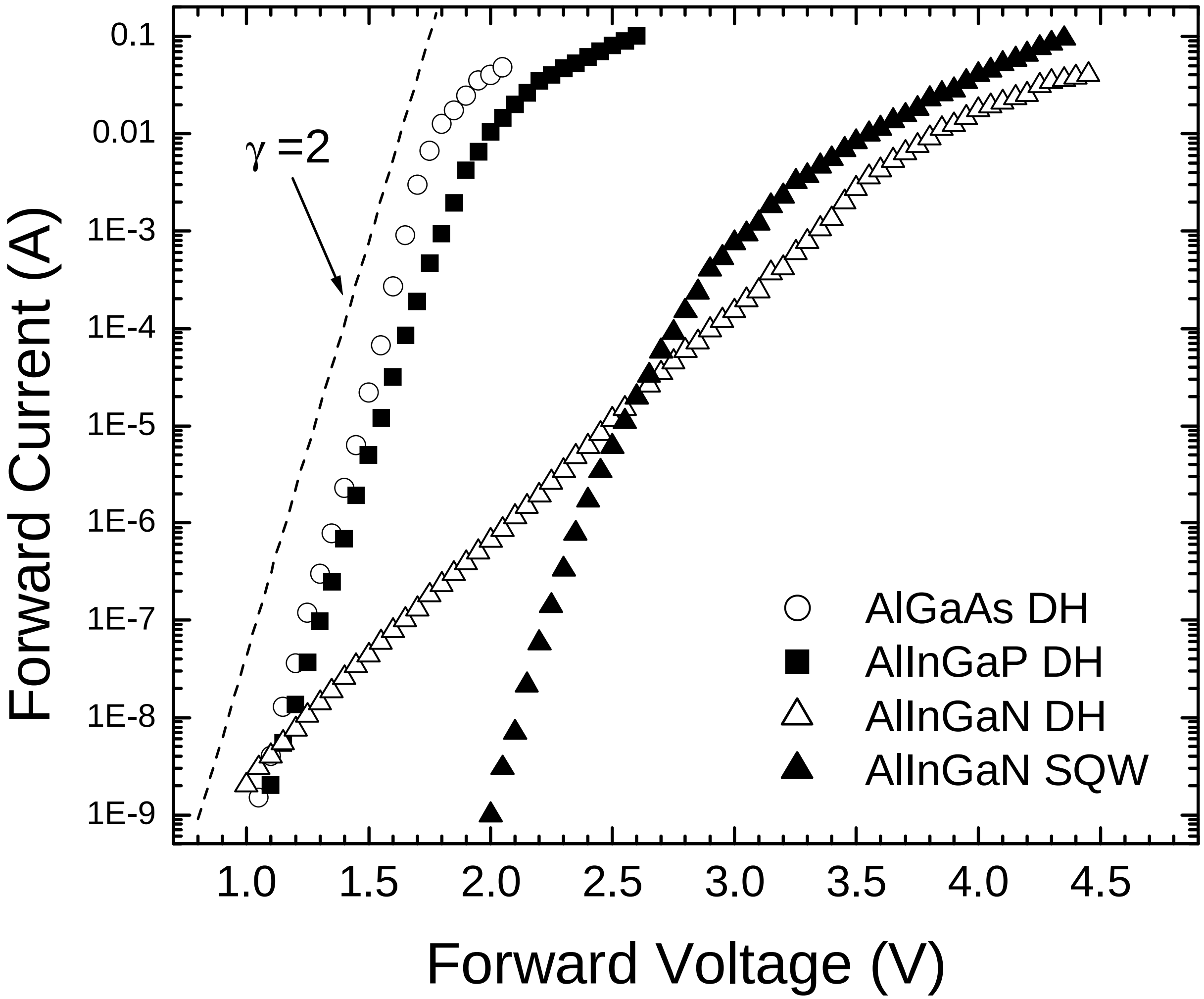
Emission line peak position vs. forward current in high brightness LEDs



Output characteristics in AlGaAs, AlGaInP and AlInGaN-based LEDs. Dependences are arbitrarily shifted along vertical axis



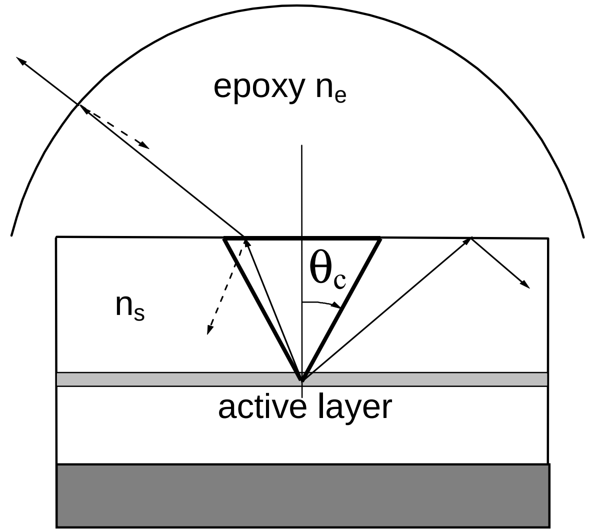
Current-voltage characteristics of AlGaAs, AlGaInP, and AlInGaN-based high brightness LEDs



LIGHT EXTRACTION FROM LEDs

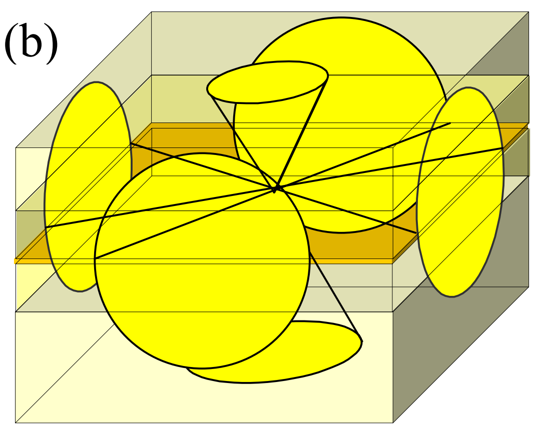
Challenges in light extraction

Conventional LED chip grown on an absorbing substrate. the apex .



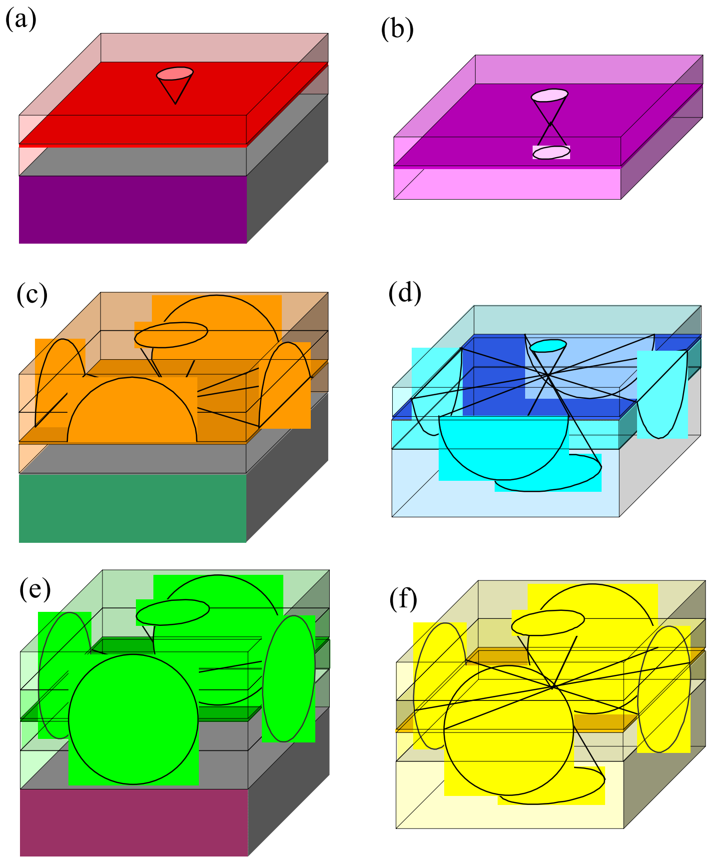
High-brightness LED chip design with thick transparent window layers. Light escapes through 6 cones

(b)

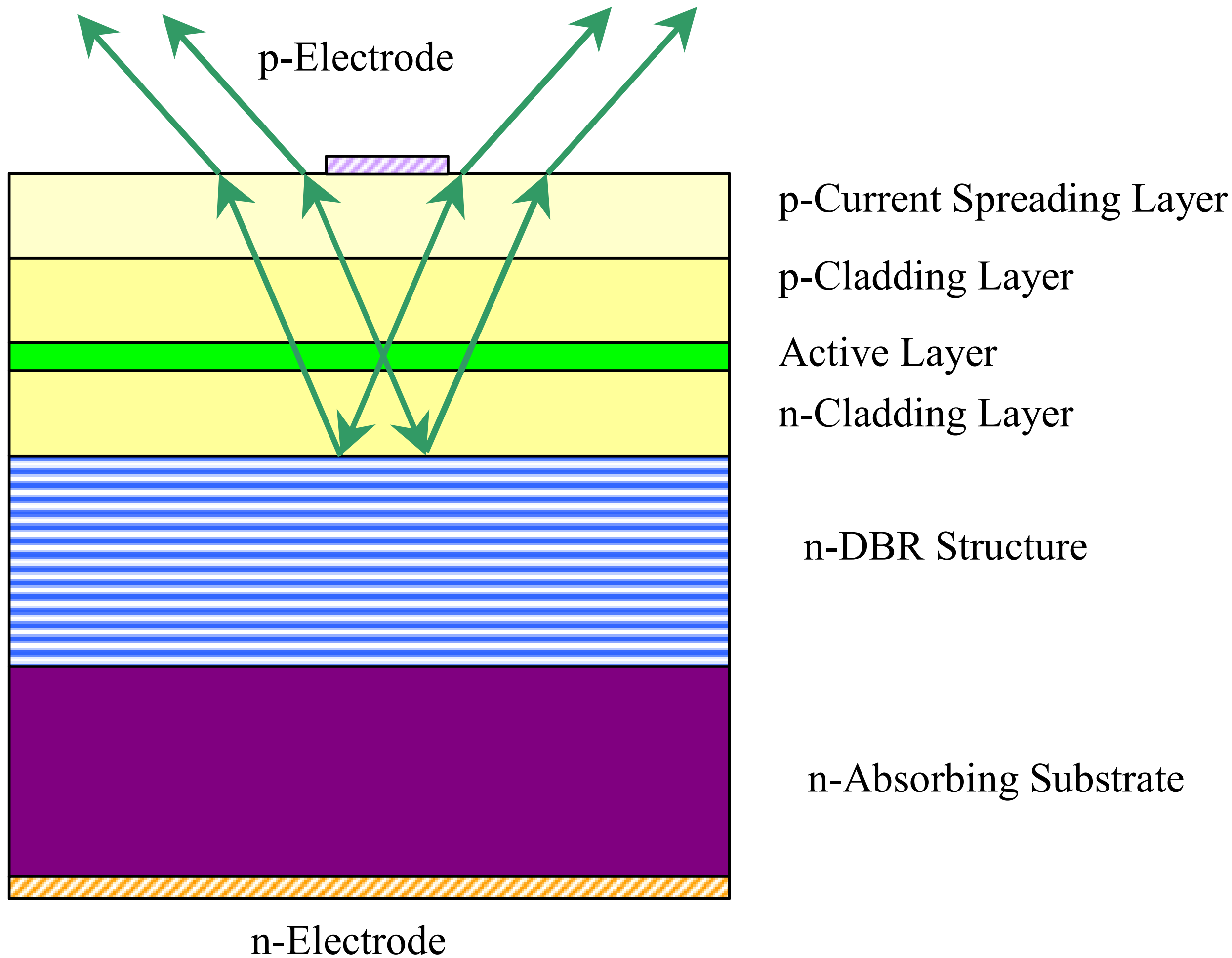


From A.Žukauskas *et al., MRS Bull.* **26**, 764, 2001.

LED Designs with Different Numbers of Escape Cones



Distributed Bragg Reflectors



Absorption Losses and Photon Recycling

- Most of the losses are due to the absorption in the active layer and in the surrounding transparent cladding and window layers

- The losses in the active layer depend on the probability of the light reemission: absorbed photons can experience reincarnation and get a new chance to find the escape cone.

- If the internal quantum efficiency is high, the photon would be recycled many times until it escapes

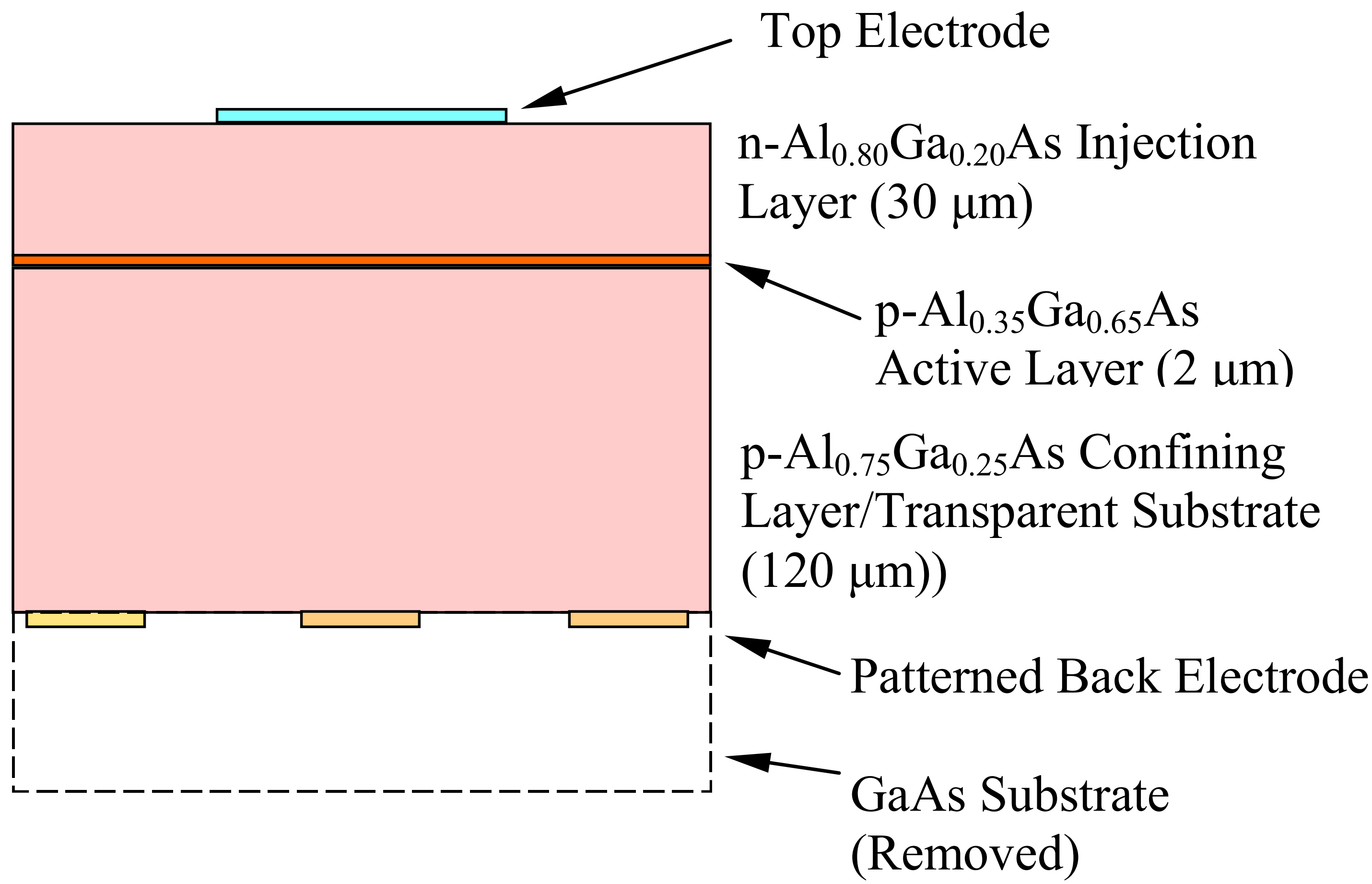
- (Theory of the photon recycling in LEDs is discussed by T.Baba *et al., Jpn. J. Appl. Phys.* **35,** 97, 1997 and references therein).

External Quantum Efficiency and Active Layer

- 72% external quantum efficiency was demonstrated in an optically pumped AlGaAs/GaAs double heterostructure mounted on a high-reflectivity surface (I. Schnitzer *et al., Appl. Phys. Lett.* **63**, 2174, 1993).
- Multiple recycling of the photons was due to the internal quantum efficiency as high as 99.7%.
- In practical LEDs, the internal quantum efficiency is lower than 100% and the absorption in the active layer is often considered as parasitic. Therefore, thin active layers (homogenous or comprised of multiple wells) are often preferred.

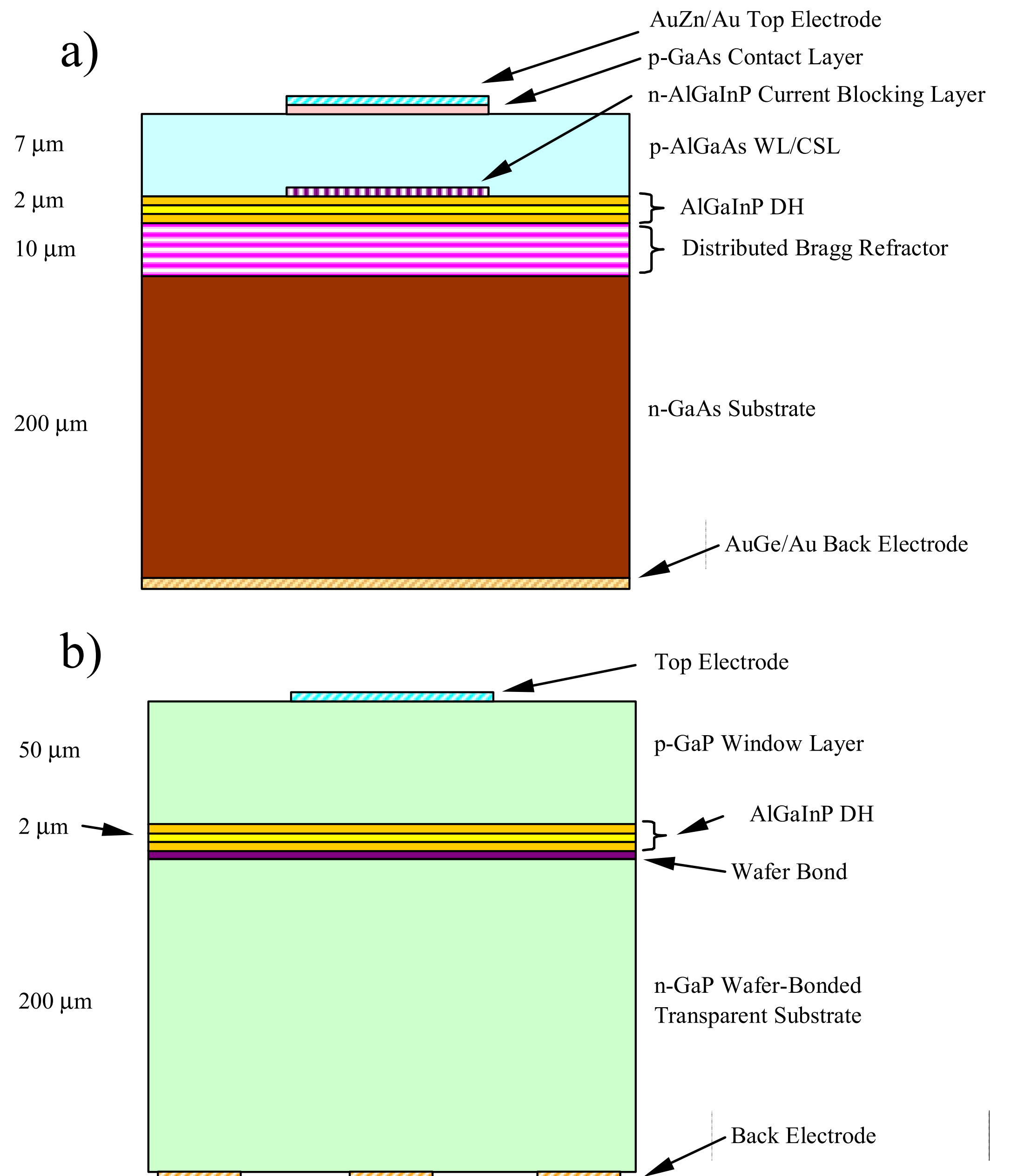
- There is an optimum active layer thickness because of a trade-off between the active-layer reabsorption and electron confinement, and this thickness depends on the emission wavelength
- (Gardner *et al., Appl. Phys. Lett.* **74** (15), 2230, 1999).

Light extraction: high-brightness AlGaAs double heterostructure LED with transparent substrate (after F. M. Steranka, *Semiconductors and Semimetals* Vol. **48,** Academic Press, New York, 1997).



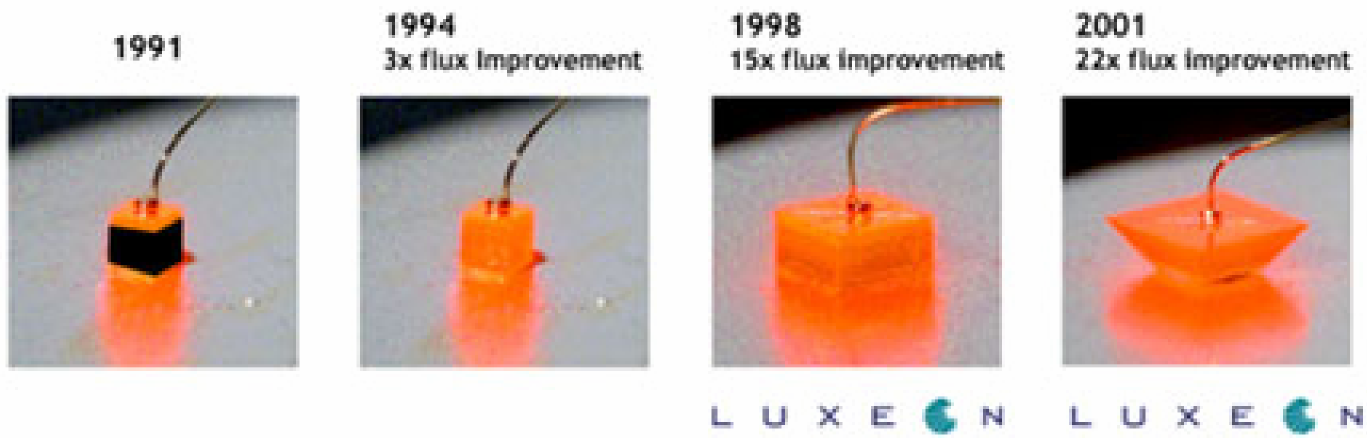
AlGaInP LEDs

(after F.A.Kish and R.M.Fletcher, *Semiconductors and Semimetals* Vol. **48,** Academic Press, New York, 1997).



Progress in AlInGaP LEDs

Lumileds LED semiconductor material
AlInGaP technology for Red, Orange and Amber colors

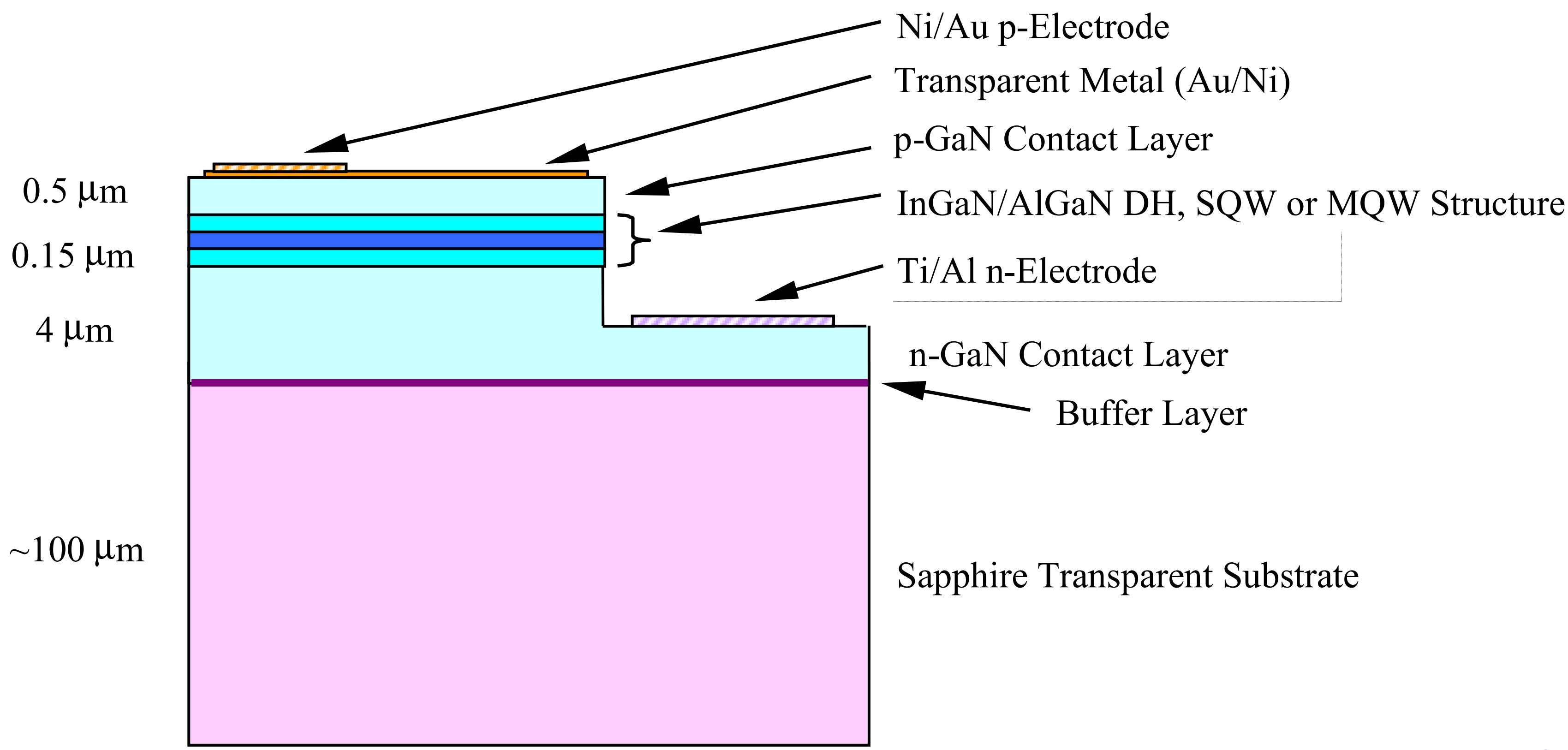


Lumileds invests heavily to develop leading technology in LED material. Our AlInGaP technology leads the world in performance for Red, Orange, and Amber light. And we continue to improve performance.

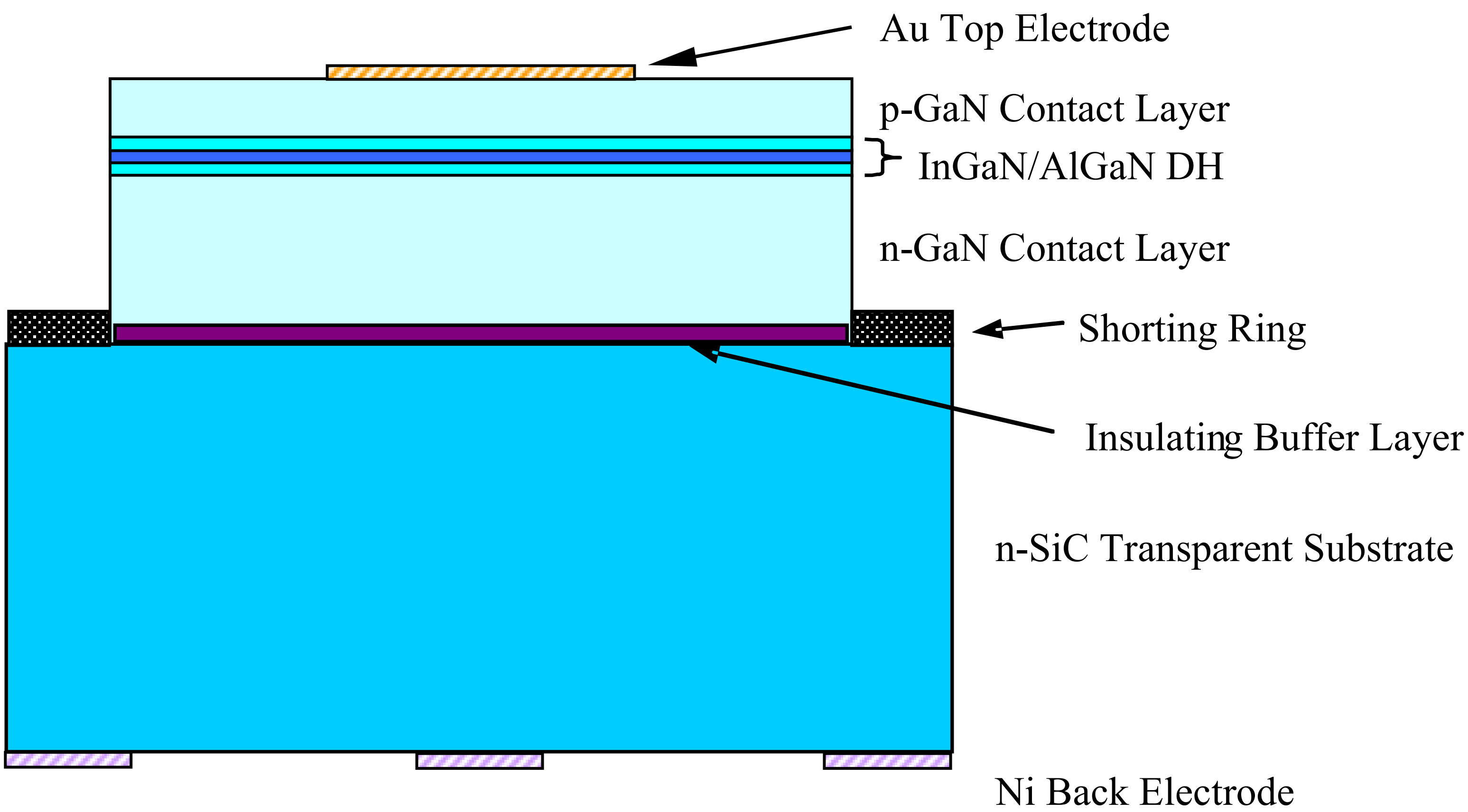
After http://www.lumileds.com/technology/tutorial/slide2.htm

Chip structure of AlInGaN/Al_2O_3 LED

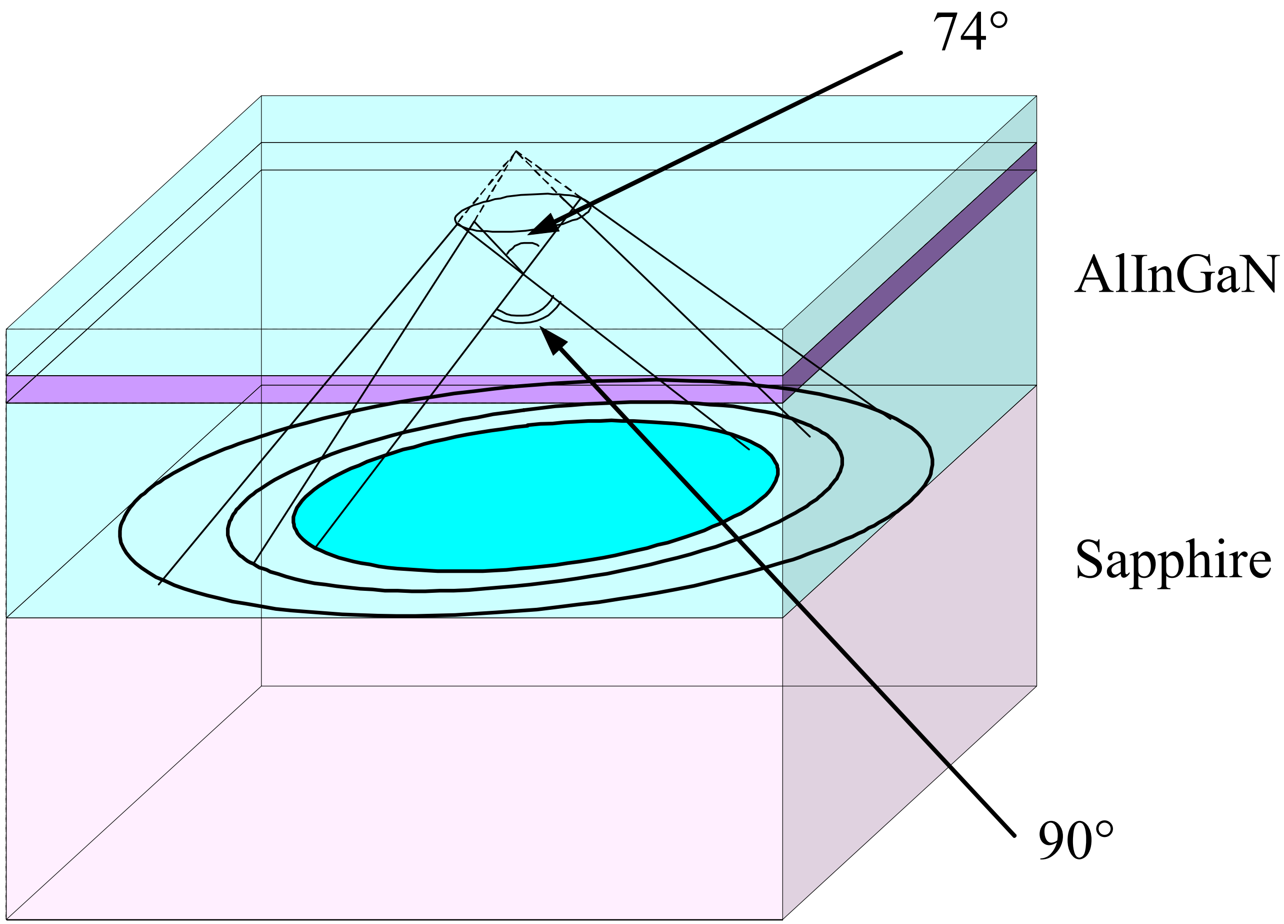
(after S.Nakamura and G.Fasol, *The Blue Laser Diode: GaN Based Light Emitters and Lasers,* Springer, Berlin, 1997).



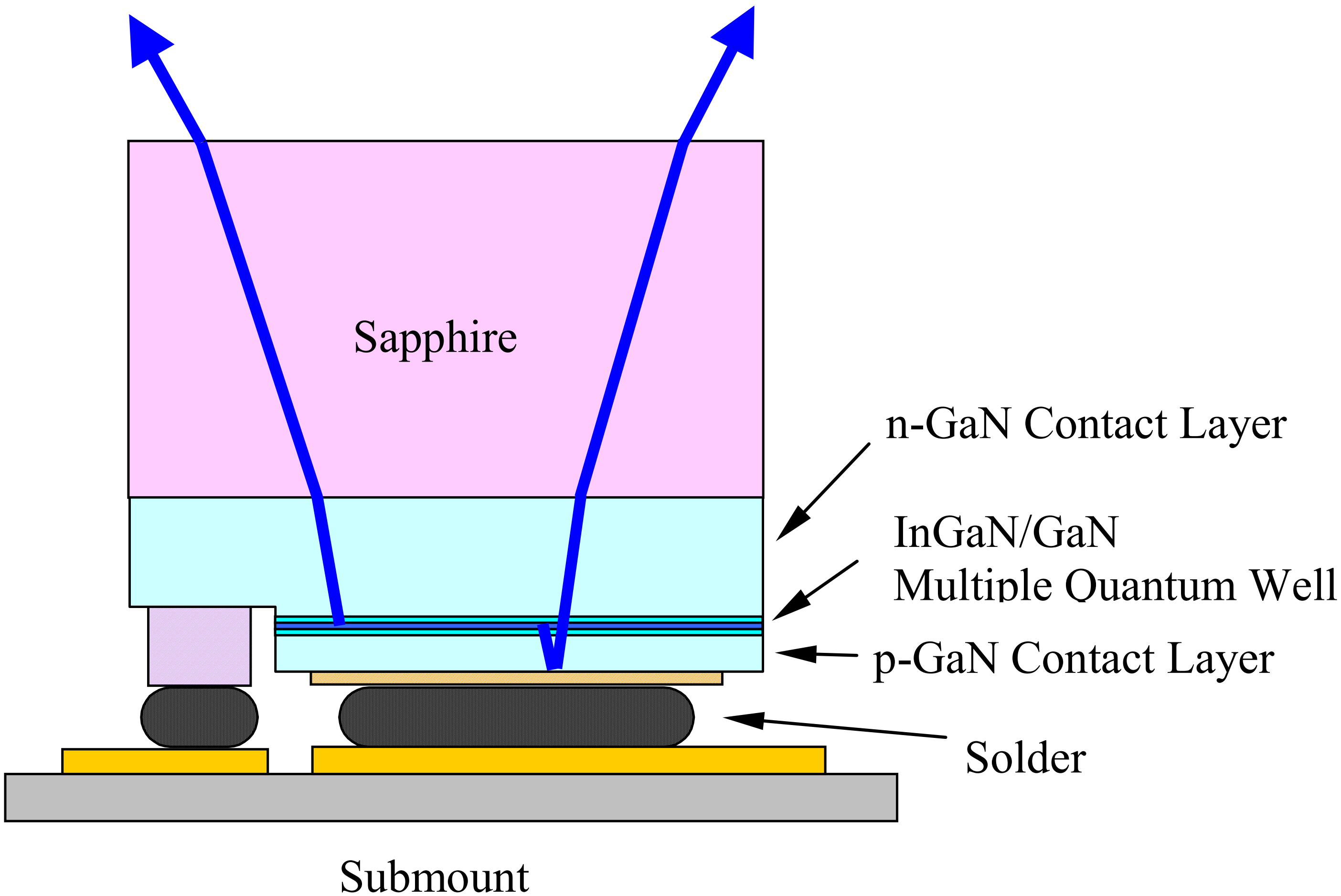
AlInGaN/SiC LED (after J.A.Edmond *et al.*, *Proc. SPIE* **3002**, 2, 1997).



Escape cones in AlInGaN-based LED chip on sapphire substrate. Apex of upward cone is 74° and apex of inner downward cone is 90°.

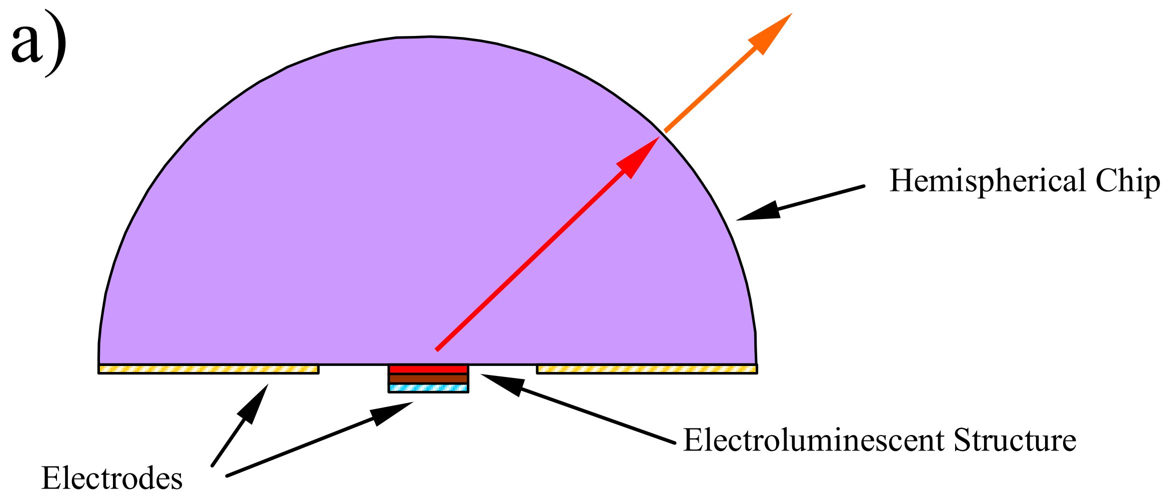


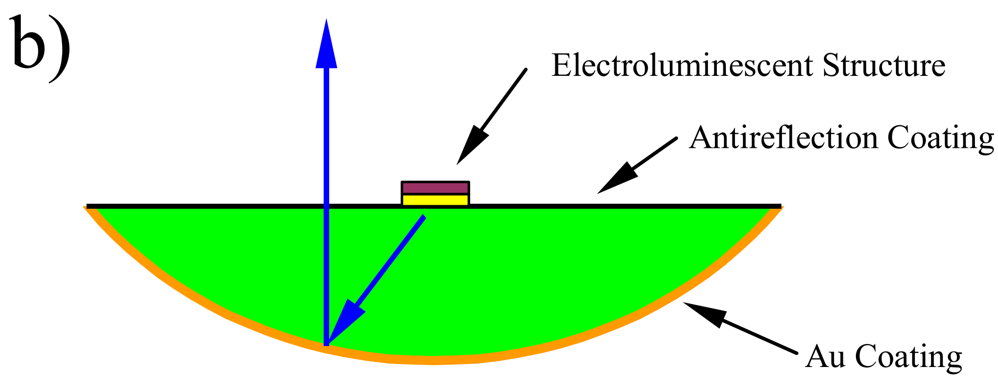
High power AlInGaN Flip-Chip LED



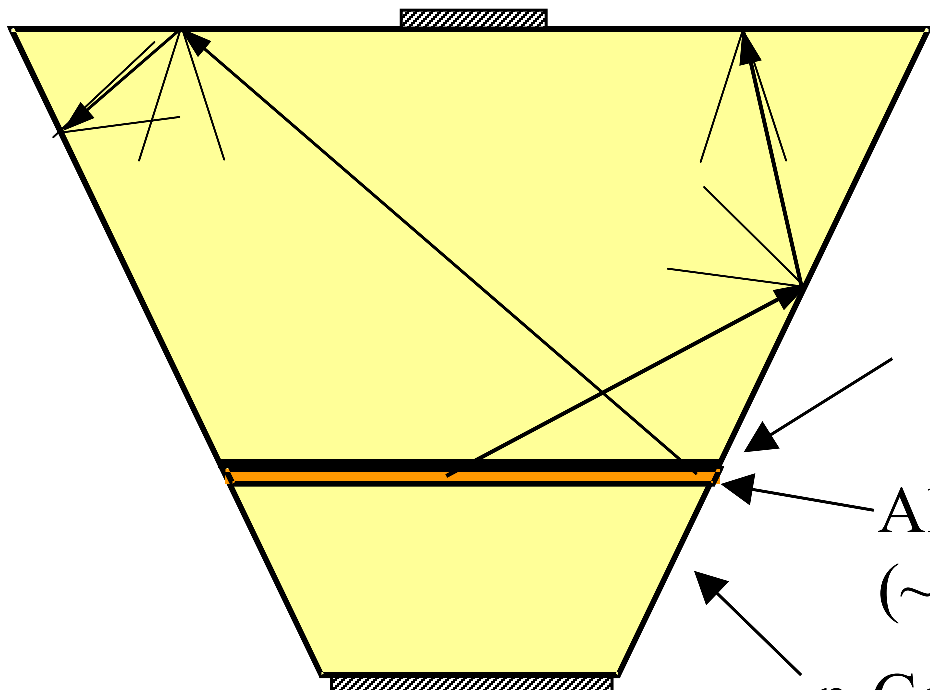
After J. J. Wieret *et al.*, *Appl. Phys. Lett.* **78,** 3379, 2001.

Shaped Chips: semi-spherical



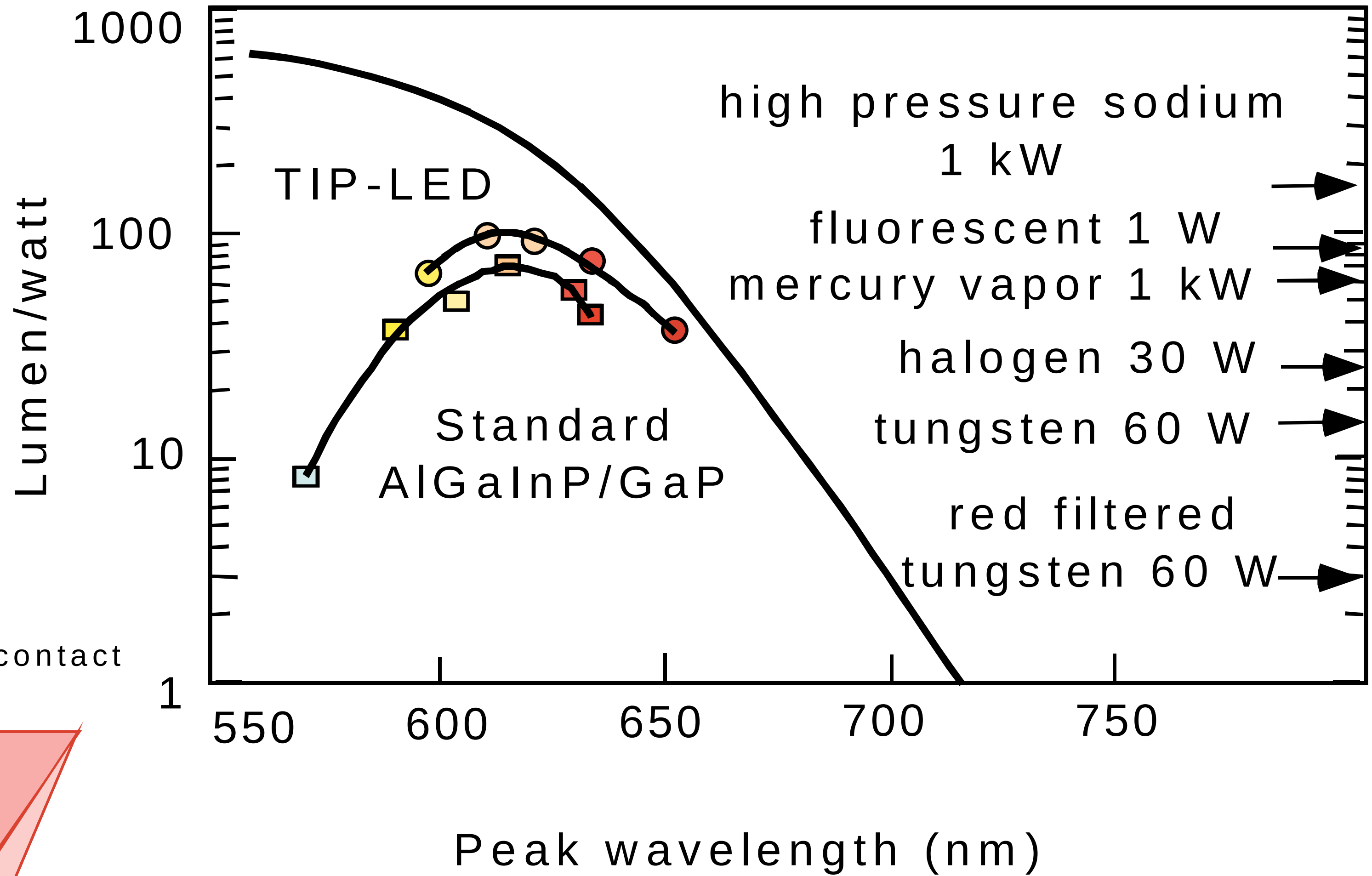


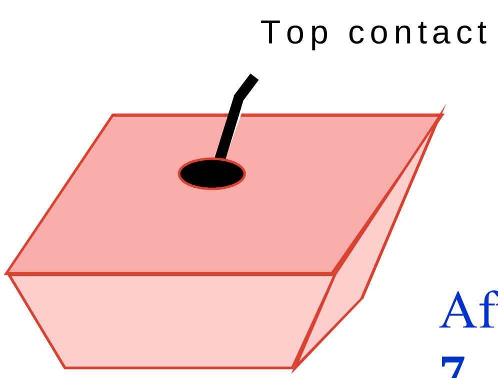
Truncated-inverted-pyramid AlGaInP/GaP LED



After M. R. Krames *et al., Appl. Phys. Lett.* **75,** 2365, 1999.

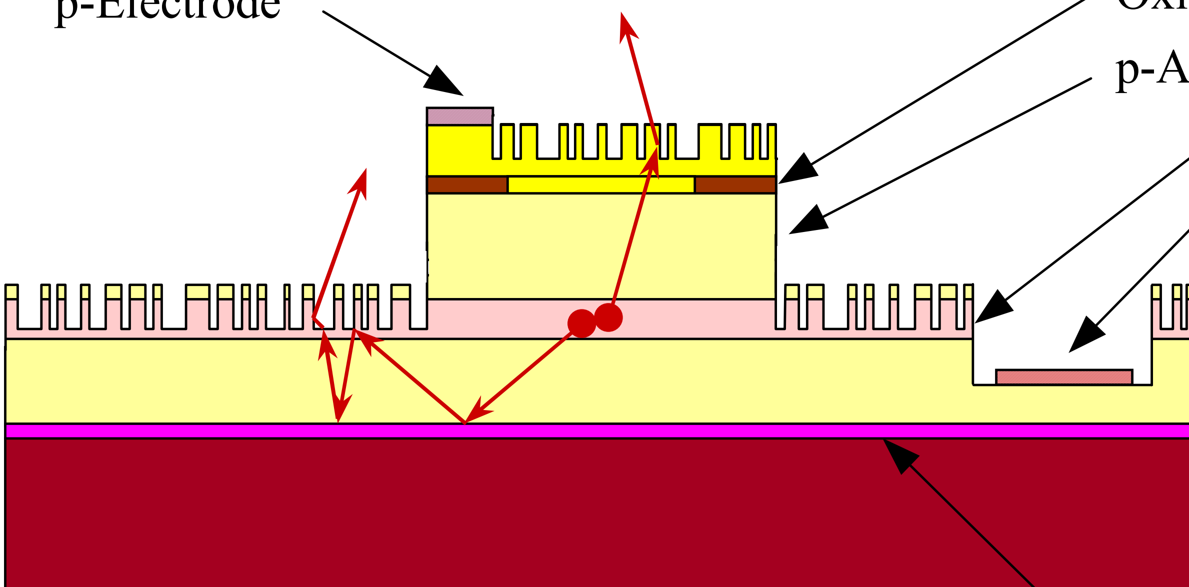
Light Extraction : TIP-LEDs from LumiLeDs





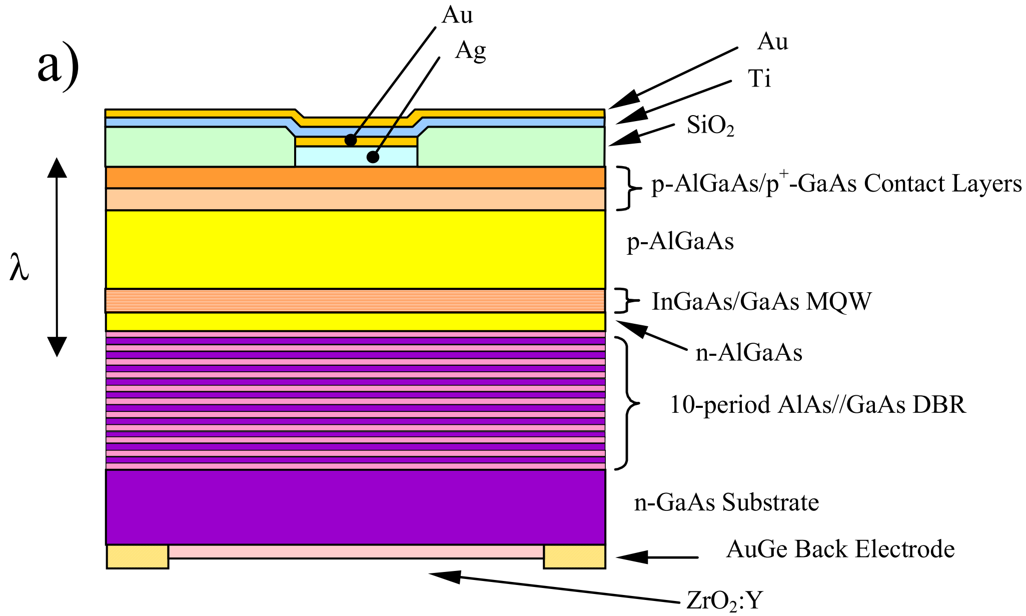
After M.O. HOLCOMB *et al.* (2001), Compound Semiconductor **7**, 59, 2001).

Non Resonant Cavity LEDs

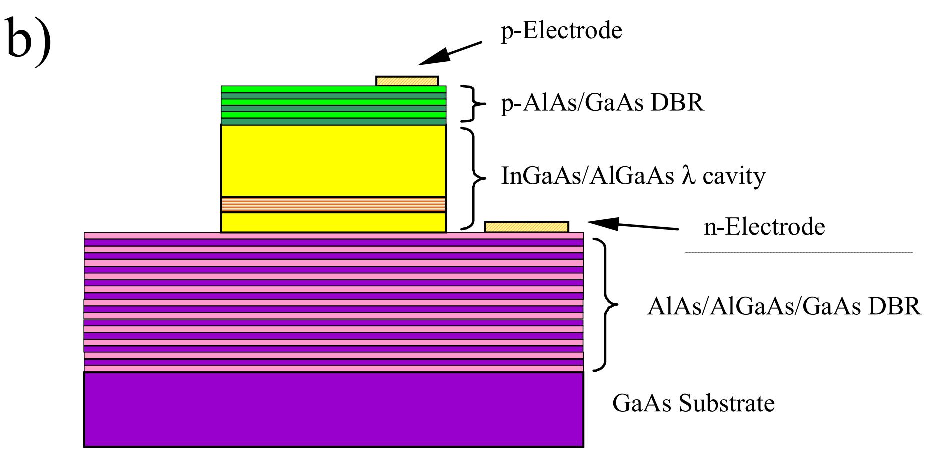


This device employs a randomly nanotextured surface for chaotization of the photon trajectories (it is mounted on a mirror) (after I. Schnitzer *et al., Appl. Phys. Lett.* **63**, 2174, 1993).

PHOTON DENSITY OF STATES ENGINEERING



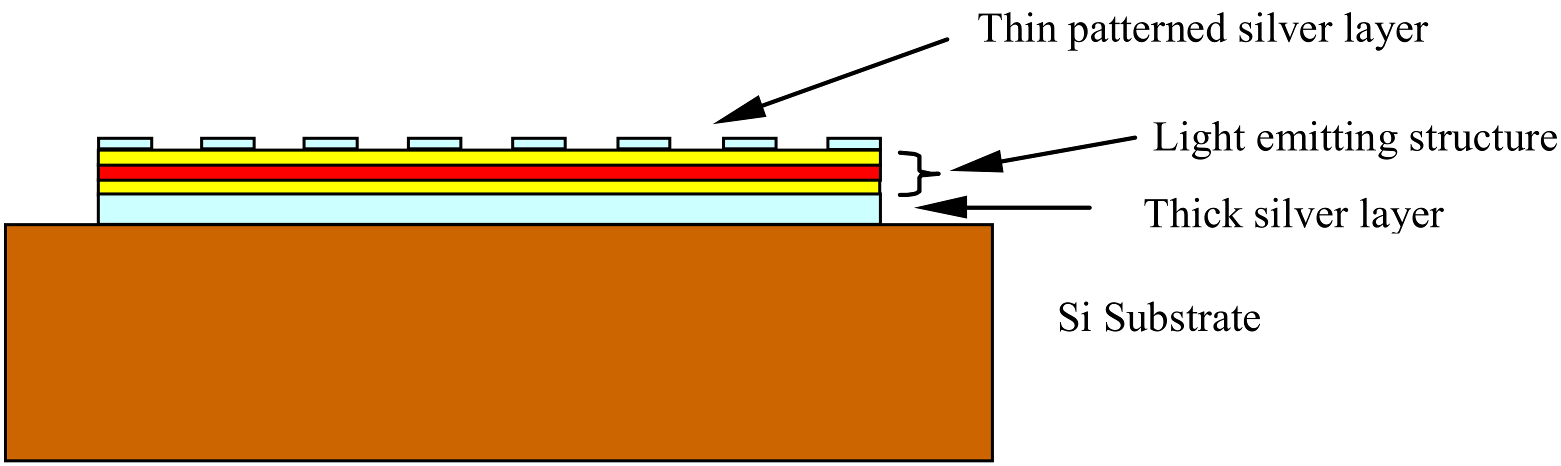
(a) Metal-mirror/DBR bottom-emitting resonant-cavity LED (after E.F.Schubert *et al.*, *Science* ***265***, *943,* 1994).



(b) DBR-DBR top emitting RC-LED (after J.F.Carlin *et al., Semicond. Sci. Tech.* ***15****,* *145*, 2000).

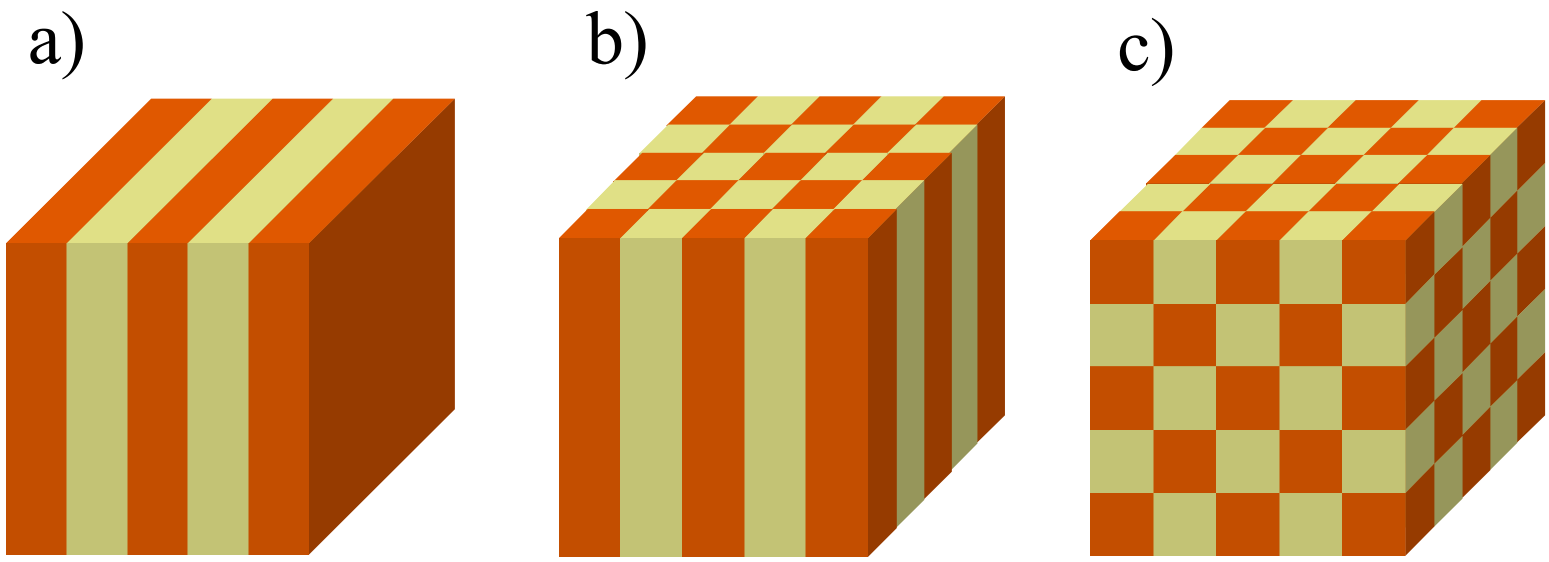
Surface plasmon enhanced LED

(after J.Vučković *et al., IEEE J. Quantum Elect.* **36**, 1131, 2000).

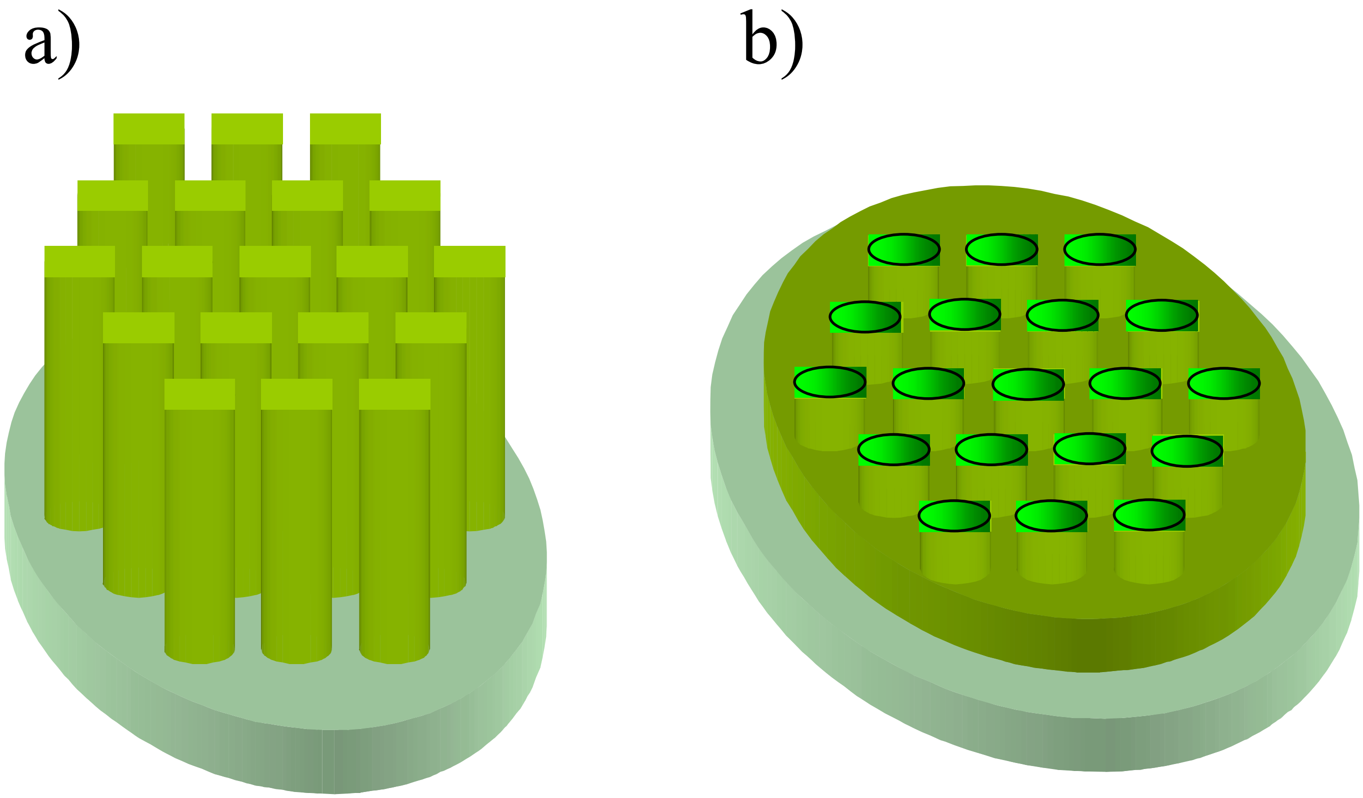


Photonic Crystals

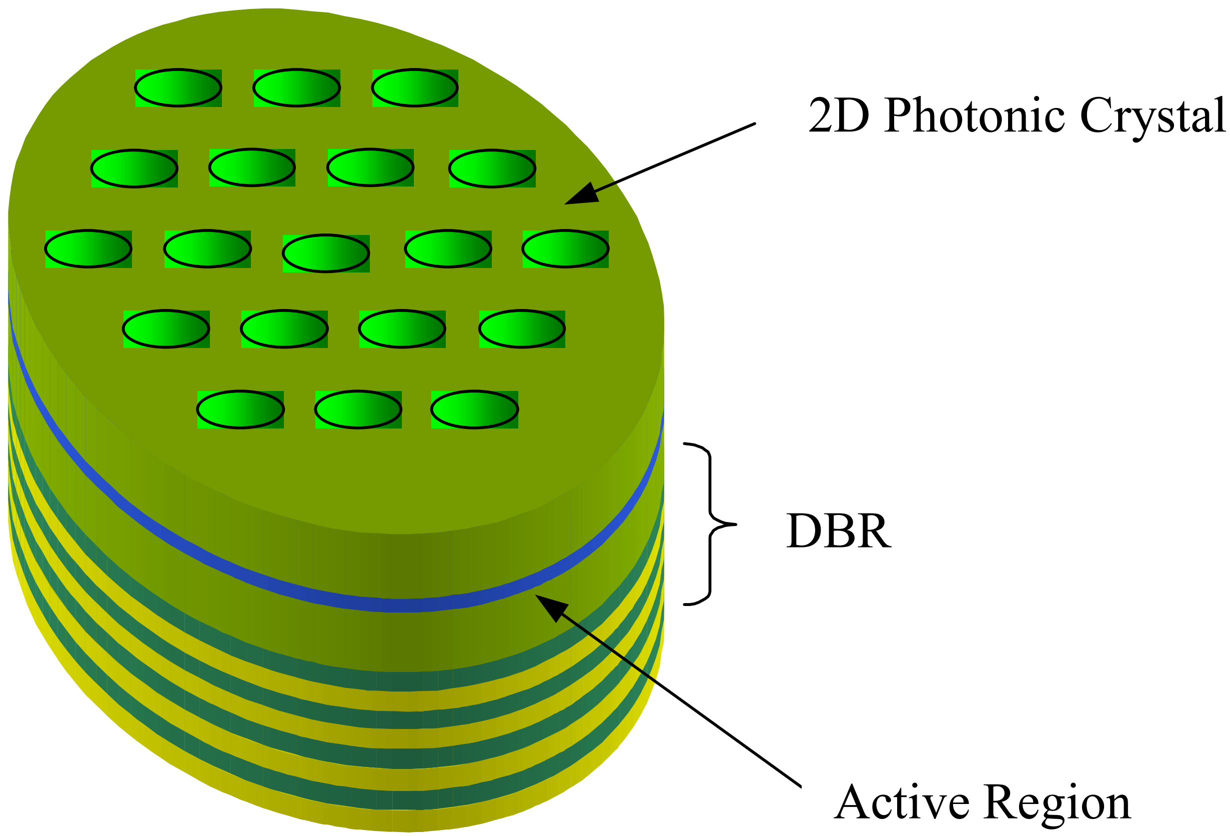
(after J.D.Joannopoulos, *Photonic Crystals: Molding the Flow of Light,* Princeton University Press, Princeton, N.J., 1995).



2D Photonic Crystals



Semiconductor light-emitting device with 2D photonic crystal and DBR structure (after T.Baba, *IEEE J. Sel. Top. Quant.* **3**, 808, 1997 and S.Fan *et al.*, *Proc. SPIE* ***3002****, 67,* 1997).



WHITE SOLID-STATE LAMP

CRI for White Light

$$K = 683\ \text{lm/W} \times \int_{380}^{780} V(\lambda)S(\lambda)d\lambda \Big/ \int_{0}^{\infty} S(\lambda)d\lambda \ ,$$

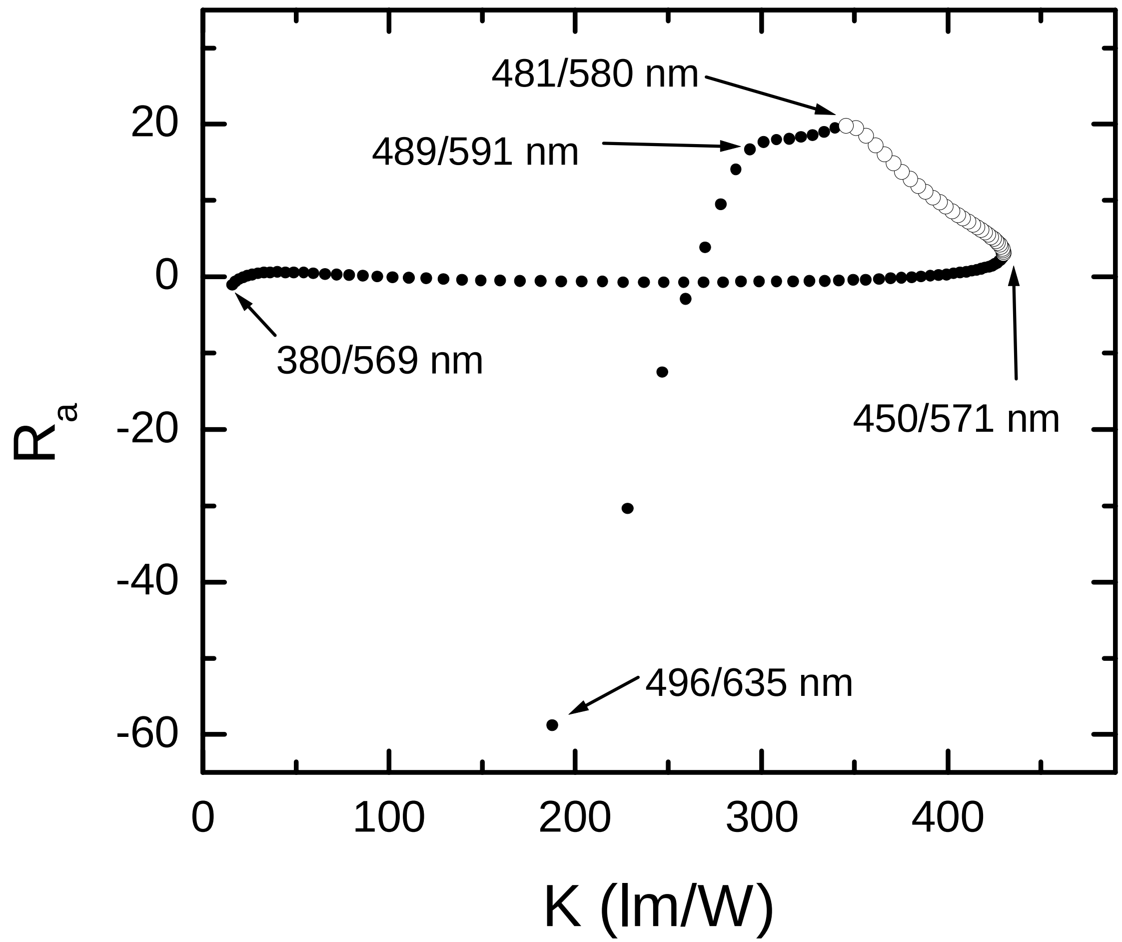
Spectral Range	Temperature (K)	Efficacy (lm/W)	General CRI
Full (Planckian)	2856	17	100
	4870	79	100
	6504	95	100
380 nm-780 nm (trimmed-Planckian)	2856	154	100
	4870	196	100
	6504	193	100
430 nm-660 nm (trimmed-Planckian)	2856	334	95
	4870	320	95
	6504	305	95

Optimization of White Polychromatic Semiconductor Lamp

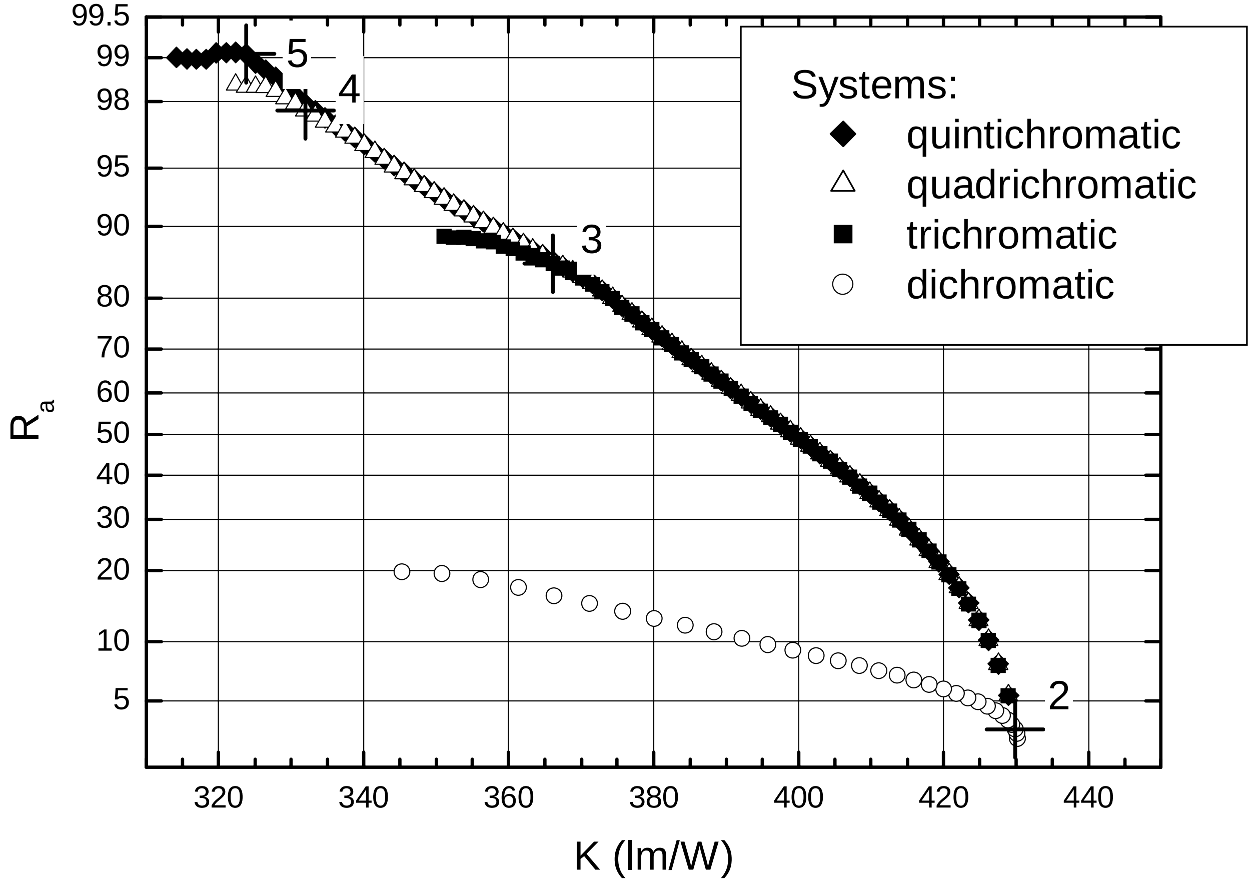
Approach: Find the global maxima of the objective function for different values of σ.

$$F_{\sigma}(\lambda_1,\ldots,\lambda_n, I_1,\ldots,I_n) = \sigma K + (1-\sigma)R_a$$

Phase distribution for a dichromatic white lamp with the 30-nm line width of the primary sources and 4870 K color temperature (after Žukauskas *et al.*, Appl. Phys. Lett. **80**, 2002).

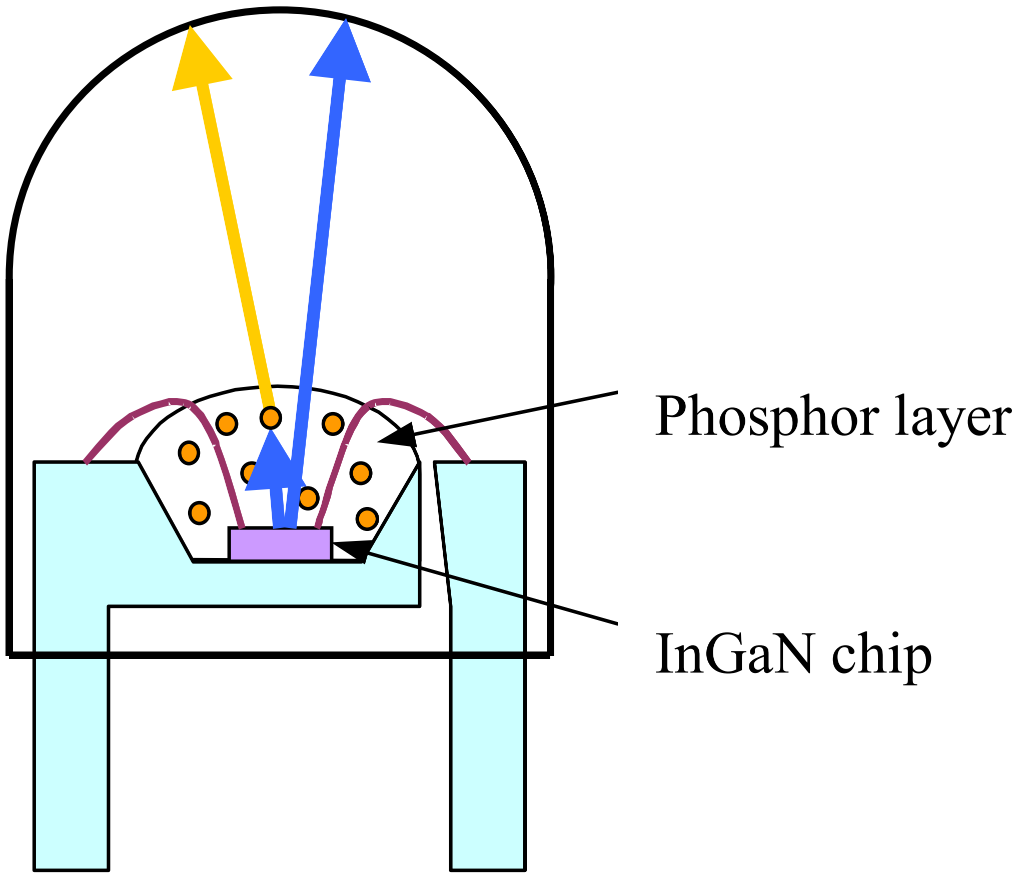


Optimal boundaries of the phase distribution for 4870-K white-light sources containing 2, 3, 4, and 5 primary sources with the 30-nm line widths (after Žukauskas *et al.*, Appl. Phys. Lett. **80**, 2002). Crosses mark the points that are suggested for highest reasonable CRI for each number of the primary sources.

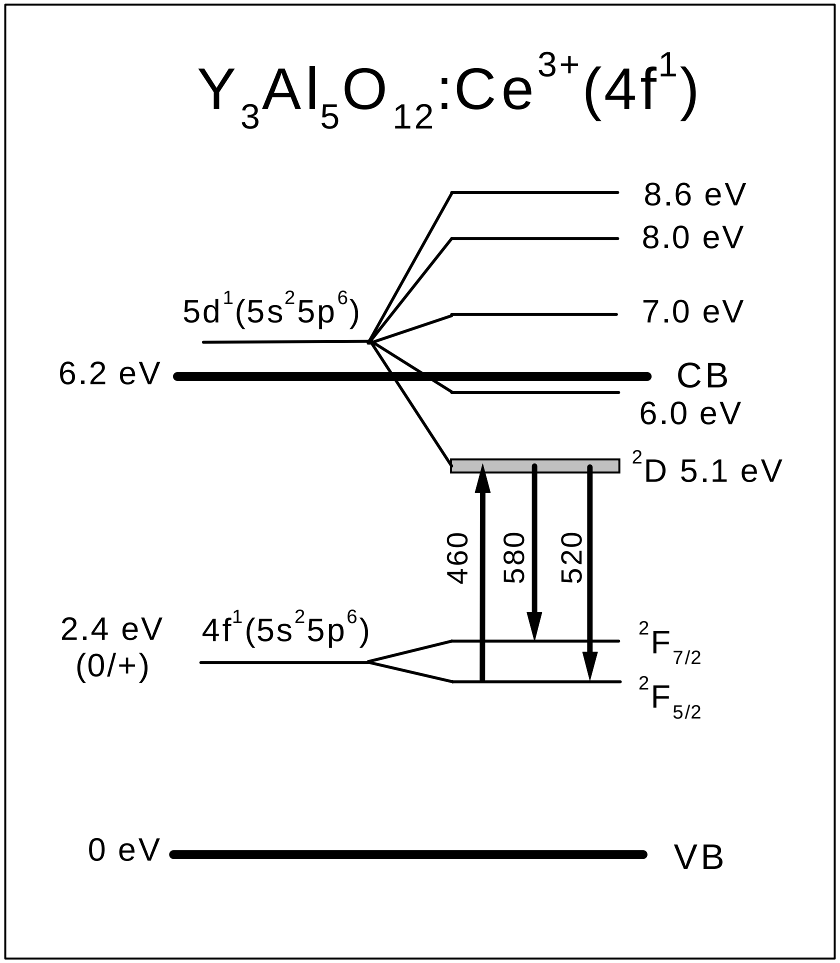


InGaN based luminescence conversion white LED

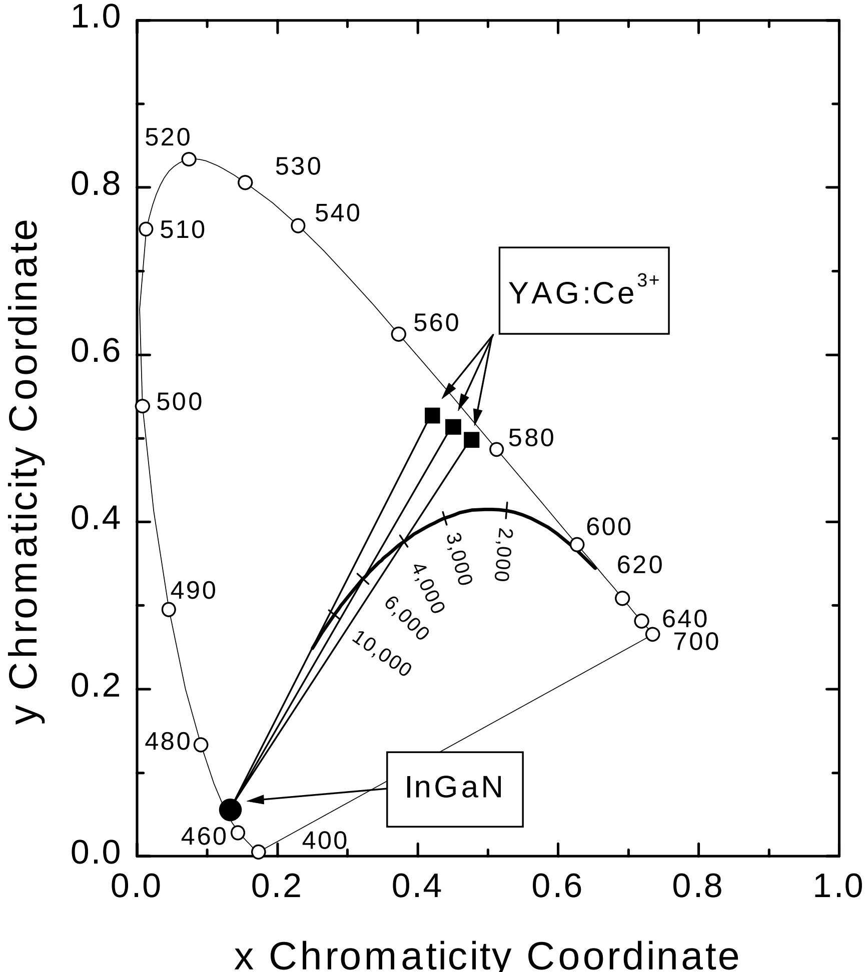
(after S.Nakamura and G.Fasol, *The Blue Laser Diode: GaN Based Light Emitters and Lasers,* Springer, Berlin, 1997)



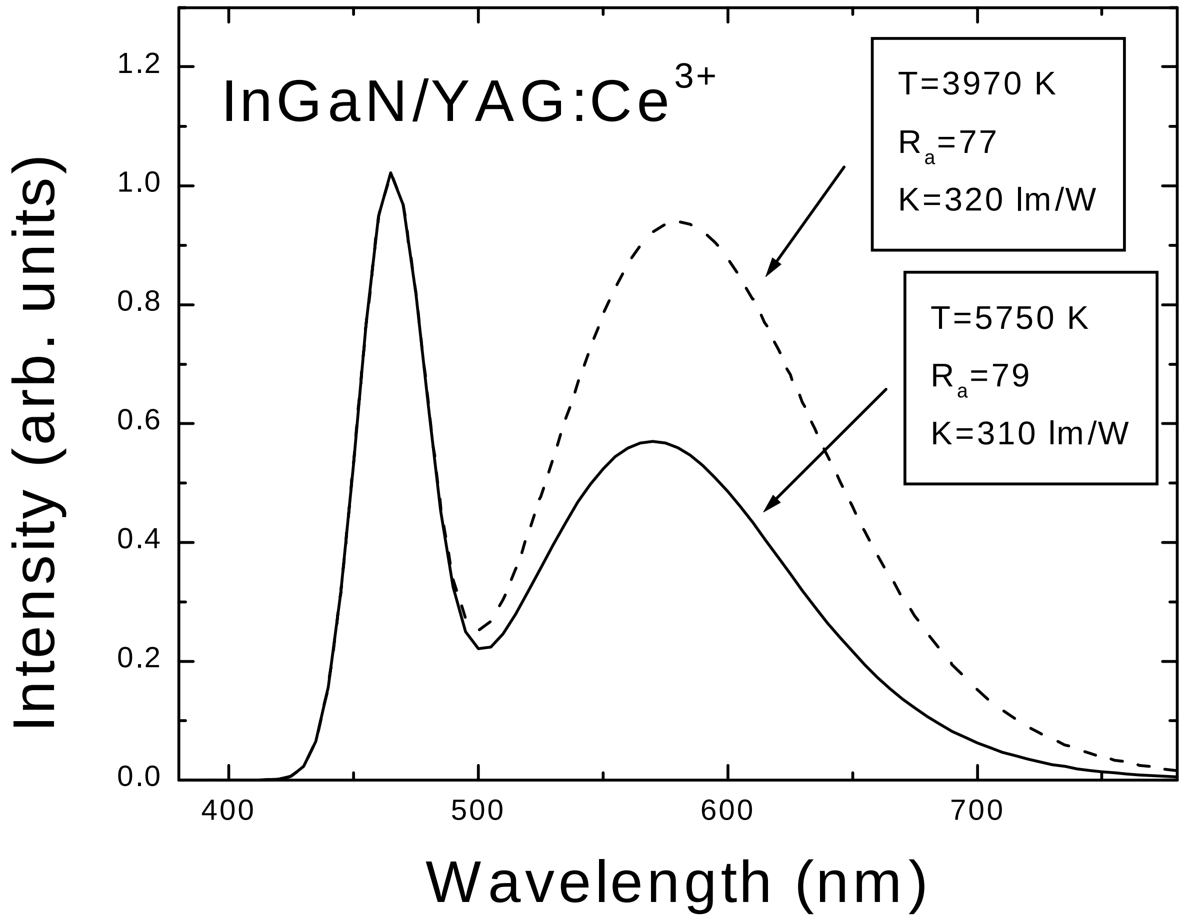
Energy levels of Ce3+ (4f1) in yttrium aluminum garnet Y3Al5O12 (after M.Batenschuk *et al.*, *MRS Symp. Proc.* ***560***, *215*, 1999).



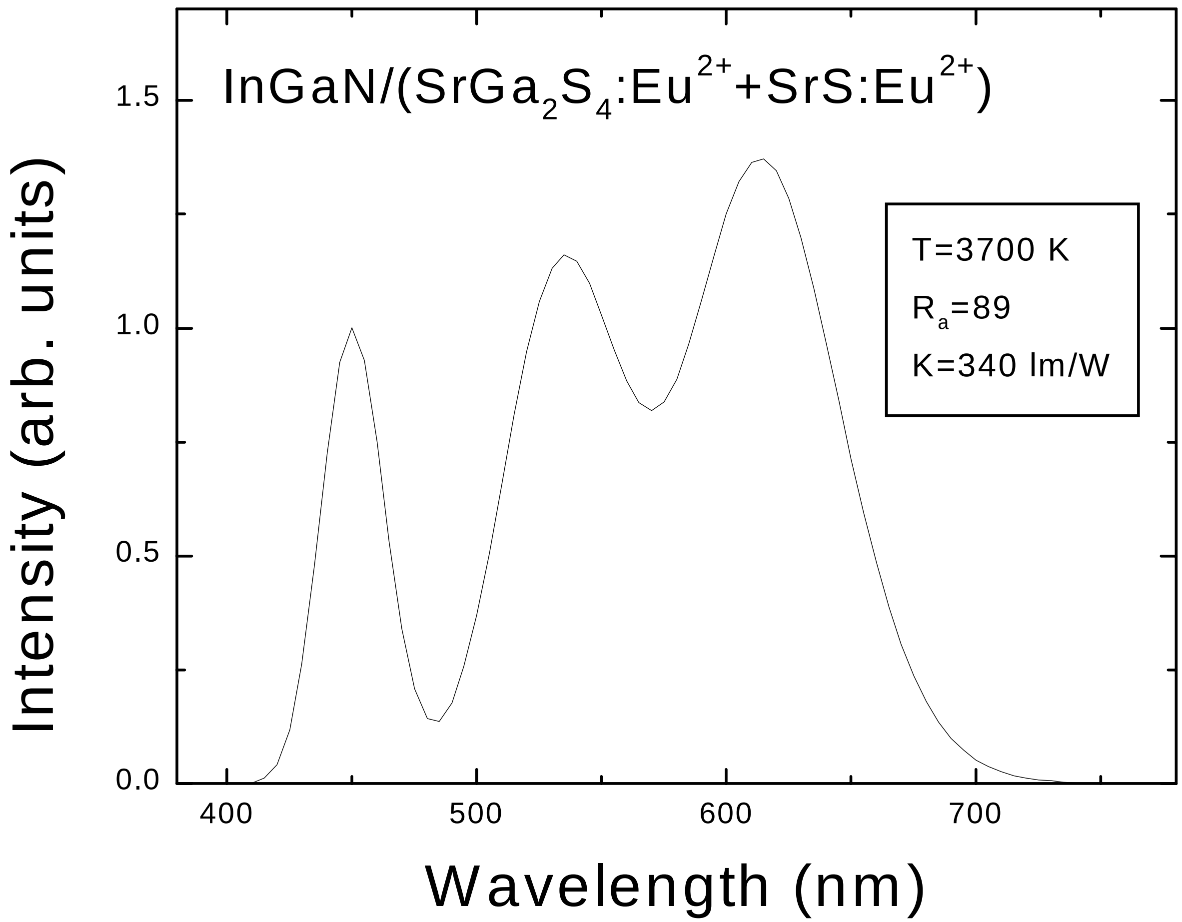
White light from blue emission of AlInGaN LED (465 nm) and yellow emission of cerium-doped garnet with different peak wavelength positions



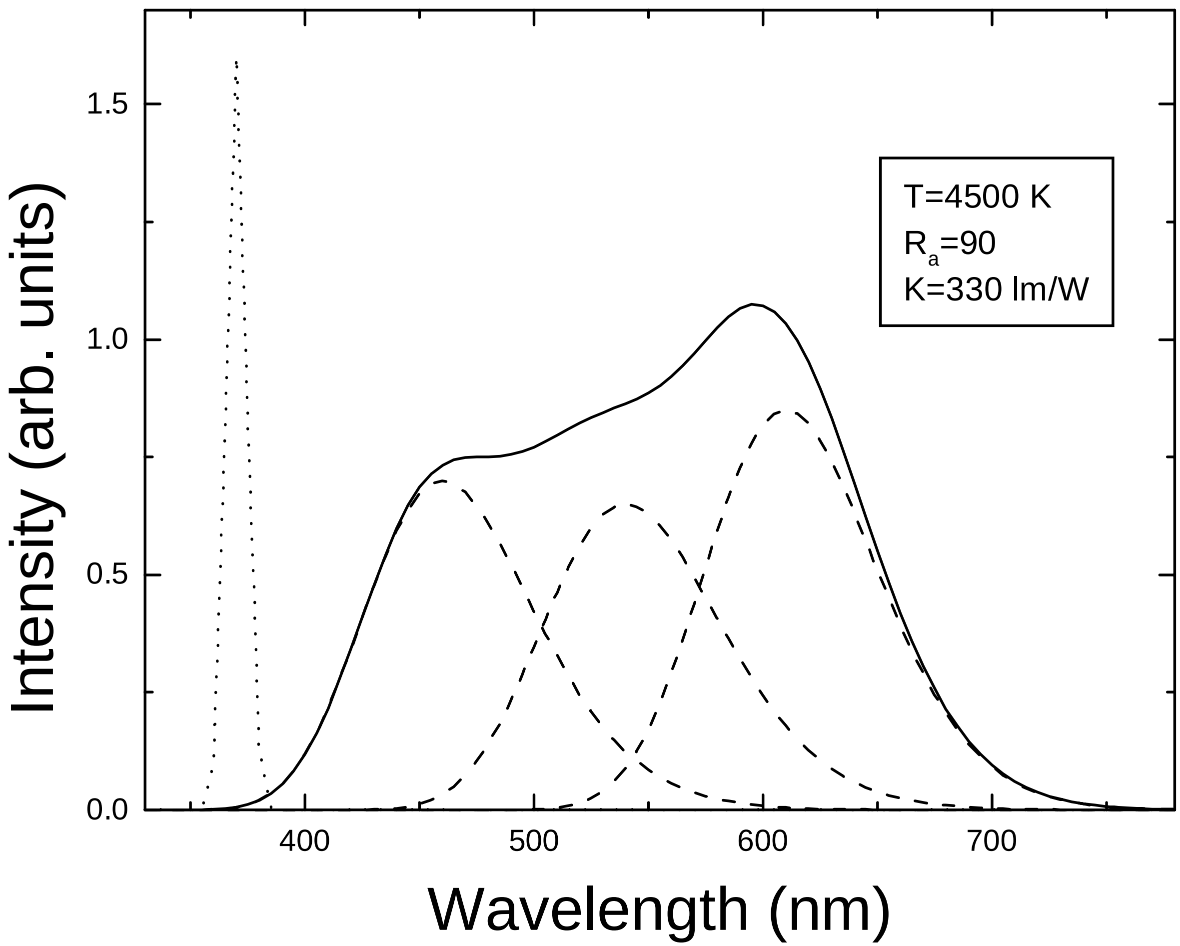
Model emission spectra of AlInGaN/(Y1-aGda)3(Al1-bGab)5O12:Ce3+ white LEDs for two compositions of garnet. Solid line, peak wavelength of phosphor emission is at 570 nm; dashed line, for 580 nm



Model white emission spectrum from AlInGaN/(SrGa2S4:Eu2++SrS:Eu2+) system (after R.Mueller-Mach and G.O.Meuller, *Proc. SPIE* **3938**, 30, 2000).



Model white emission spectrum from trichromatic PC-LED with UV pump and three phosphors (after D.Eisert *et al.*, *Inst. Pure Appl. Phys. Conf. Ser.* **1**, 841, 2000).



MULTICHIP LED: 2 chip LEDs

Color Temperature (K)	Wavelength (nm)/Intensity		K (lm/W)	R_a
	λ_1/I_1	λ_2/I_2		
2856	450/0.157	580/0.843	492	-13
4870	450/0.325	572/0.675	430	3.0
6504	450/0.399	569/0.601	393	9.5

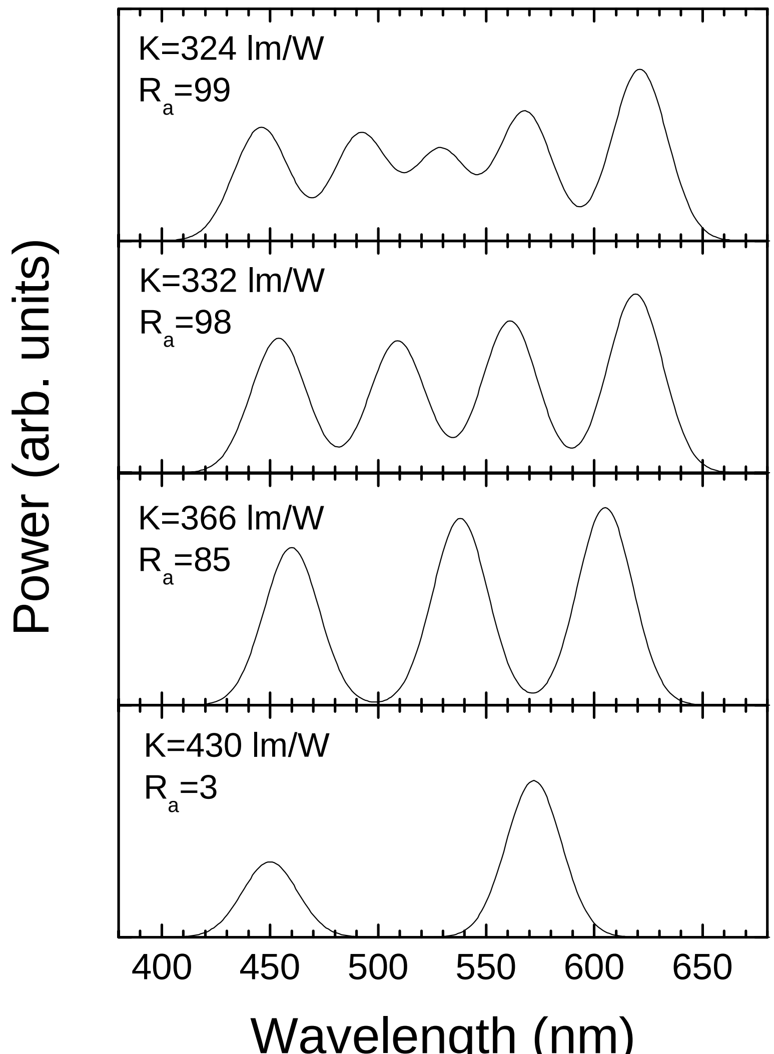
Optimized spectral power distributions

5 LEDs

4 LEDs

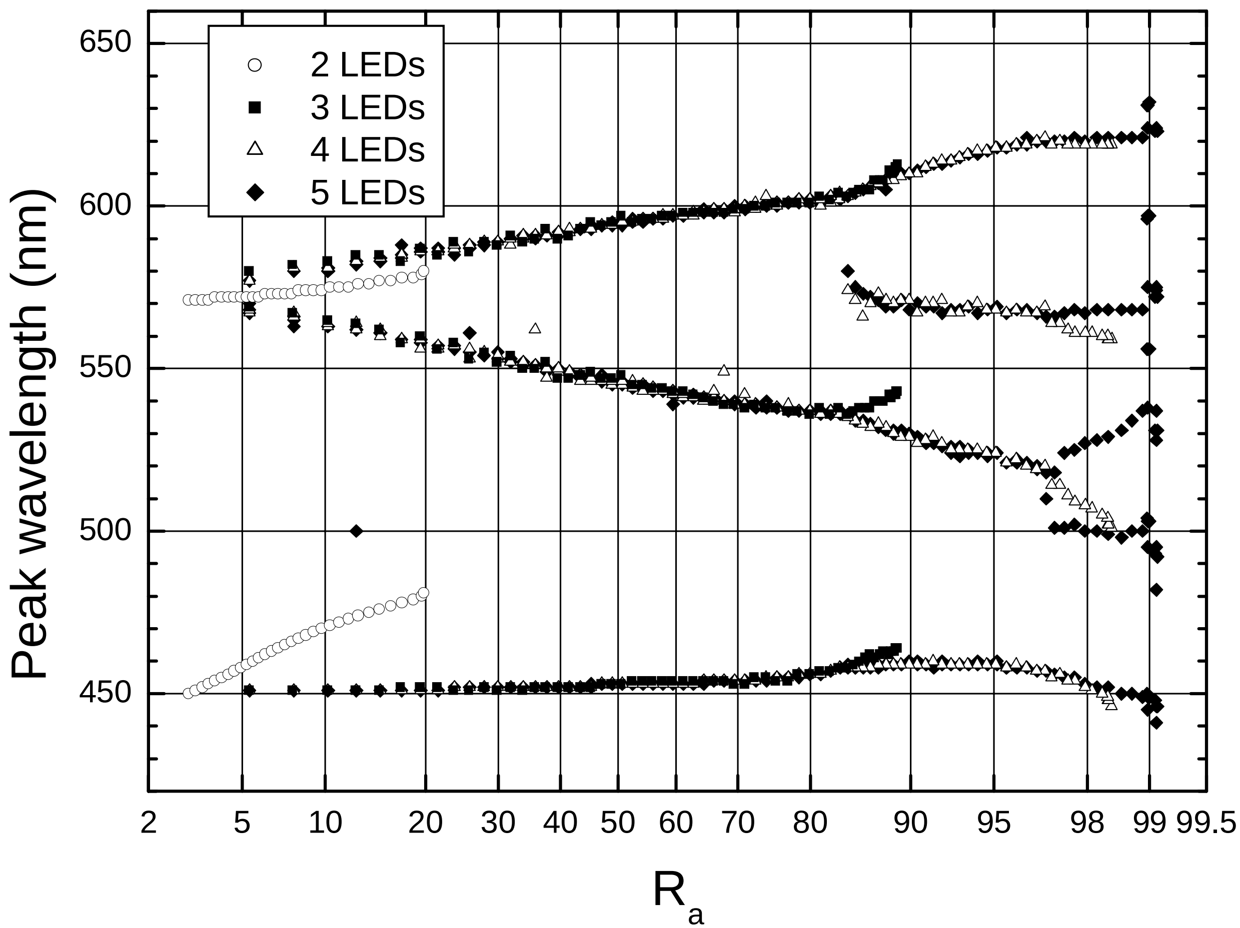
3 LEDs

2 LEDs



After
A.Žukauskas *et al.*,
Appl. Phys. Lett.
80, 2002.

Variation of the peak wavelength with general CRI for solid-state lamps composed of 2, 3, 4, and 5 primary LEDs with the 30-nm line widths (after A.Žukauskas *et al.*, *Proc. SPIE* **4425**, 2001)



Nichia LED Characteristics

Color	DC Voltage V_F[V]		I_R[µA]	P_O[mW]	Chromaticity Coordinates*	
					x	y
	Typ.	Max.	Max.	Typ.	Typ.	Typ.
BLUE	**3.6**	**4.0**	**50.0**	**6**	**0.130**	**0.075**
GREEN	**3.5**	**4.0**	**50.0**	**4**	**0.170**	**0.700**
RED	**1.9**	**2.4**	**50.0**	**2**	**0.700**	**0.300**
WHITE	**3.6**	**4.0**	**50.0**	**(4)**	**0.310**	**0.320**
Condition		I_F=20mA		V_R = 5V		

*The CIE standard colorimetric system

After http://www.nichia.co.jp/lamp-e.htm (updated June 2000)

Newer data: Dr. Zulauskas measurements: 17 mW for blue and 7 mW for green

Lumileds Laboratory Luxeon Results (2001)

Color	Luminous efficiency (lm/W)
Red	50
Red-orange	65
Amber	44
Green	50
Blue	15
White	30

After http://www.lumileds.com/technology/tutorial/slide14.htm

Lumileds Laboratory Luxeon Results (1999/2001)

Color	Lumen per LED	Date
Red	105	February 2001
Amber	110	December 1999
Green	108	March 2001
White	100.2	July 2001
White	>110	September 2001

After http://www.lumileds.com/technology/tutorial/slide15.htm

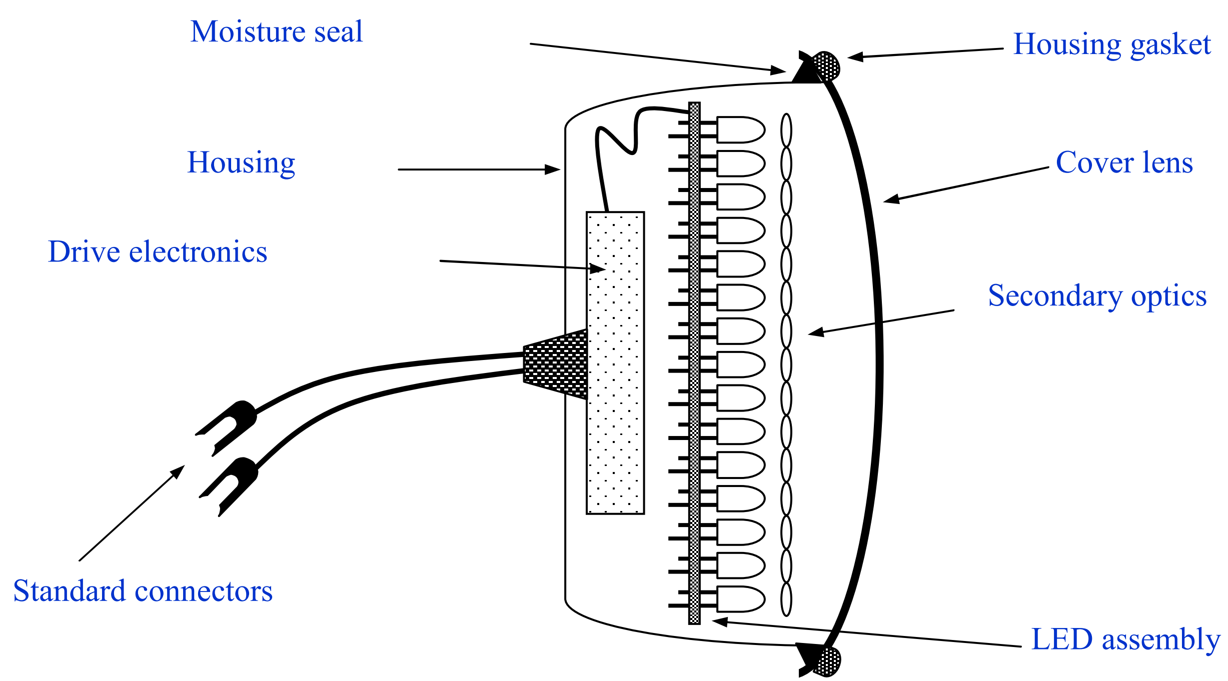
LED Applications

LED Applications
Signals and Displays

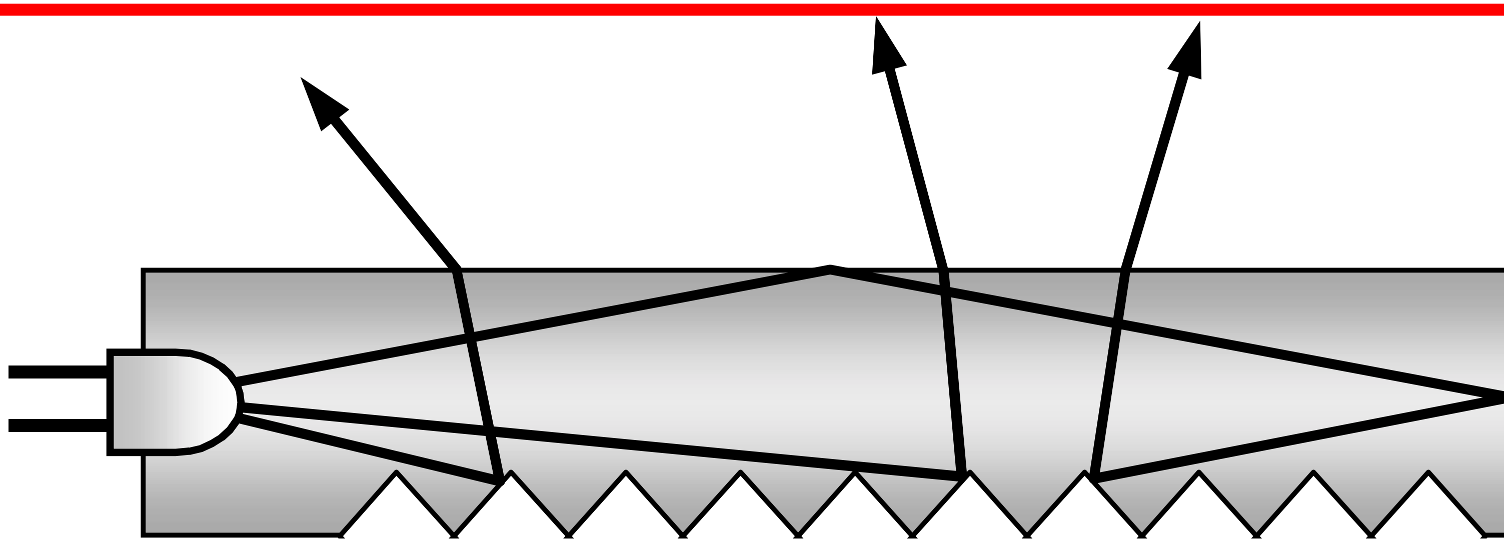
- POWER SIGNALS
  - Traffic Lights
  - Automotive Signage
  - Miscellaneous Signage

- DISPLAYS
  - Alphanumeric Displays
  - Full Color Video Displays

LED Power Signal (after D.L.Evans, *Proc. SPIE* **3002**, 142, 1997).

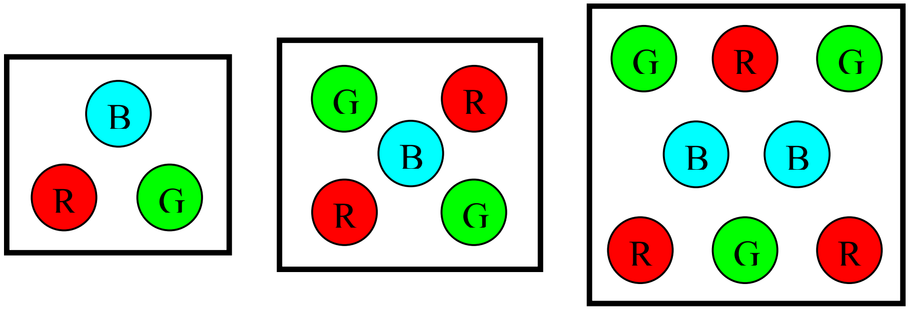


Vehicle Light Signal



After D.Decker, *Automot. Eng. Int.* **108**, 62, 2000.

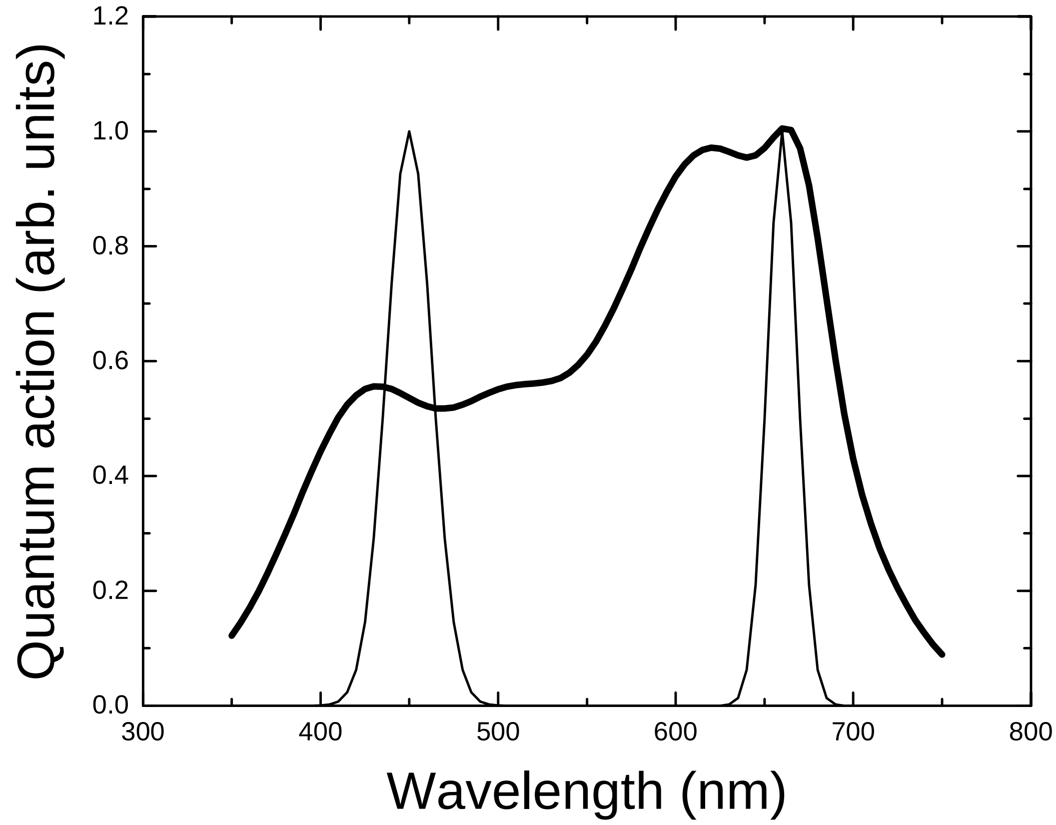
Pixels for Displays



LED Applications (Biomedical)

- MEDICAL APPLICATIONS
  - Phototherapy of Neonatal Jaundice
  - Photodynamic Therapy
  - Photopolymerization of Dental Composites
  - Phototherapy of Seasonal Affective Disorder
- PHOTOSYNTHESIS
  - Plant Growing
  - Photobioreactors
- OPTICAL MEASUREMENTS
  - Fluorescent Sensors
  - Time-Domain and Frequency-Domain Spectroscopy
  - Other Optical Applications

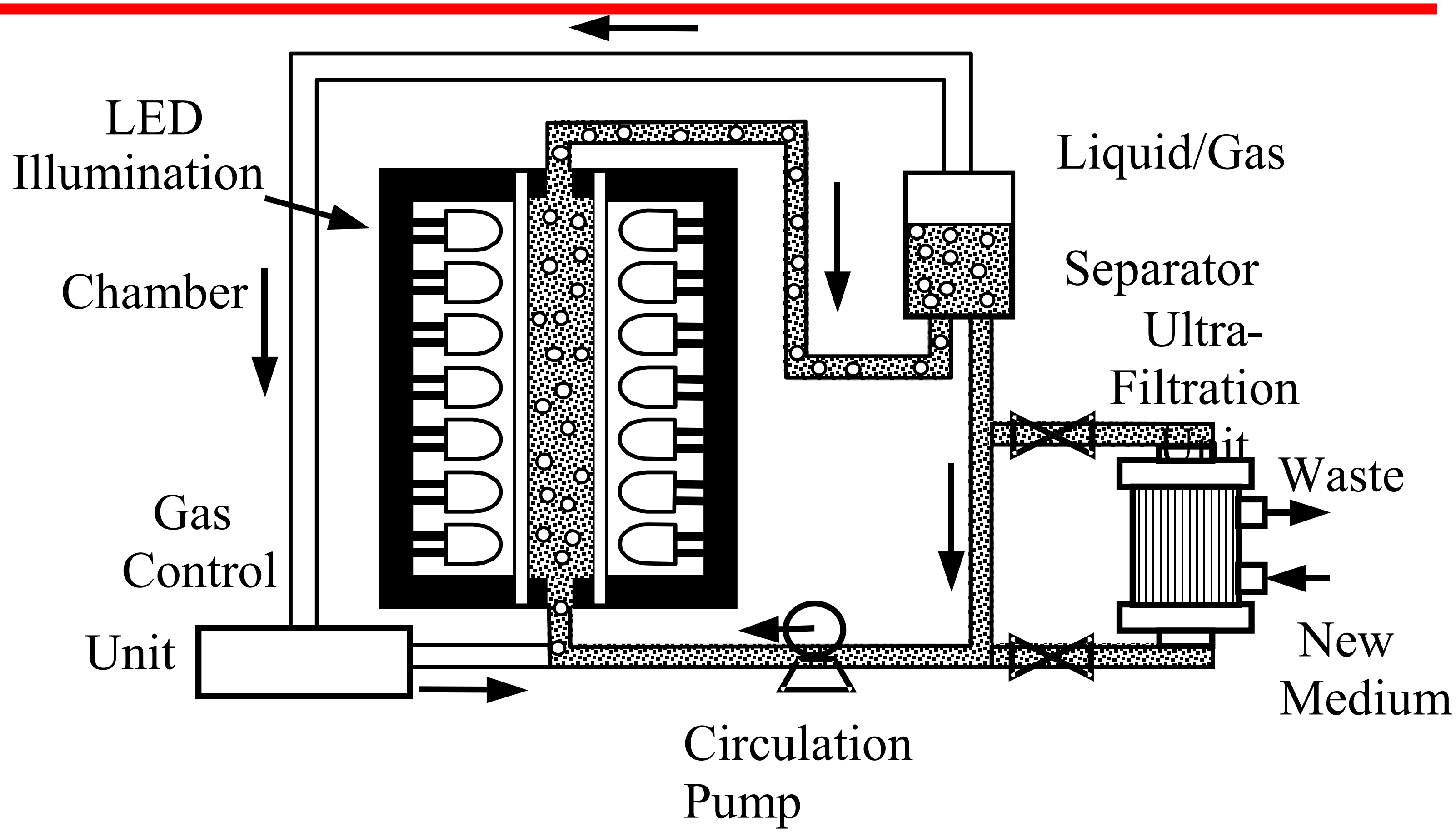
Schematic spectrum of photosynthetic quantum action of plants (after K.J.McCree, *Agr. Meteorol.* **10**, 443, 1972).



Normalized emission spectra of red AlGaAs (660 nm) and blue InGaN (450 nm) LEDs are also shown.

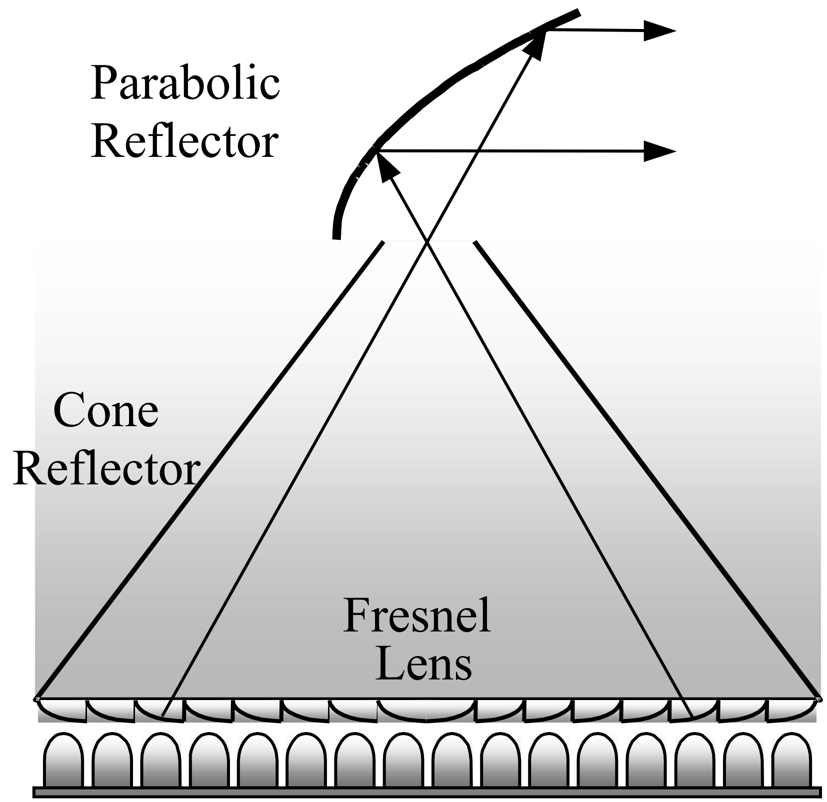
LED-based photobioreactor

(after C.-G.Lee and B.Ø.Palsson, *Biotechnol. Bioeng.* **44**, 1161, 1994)



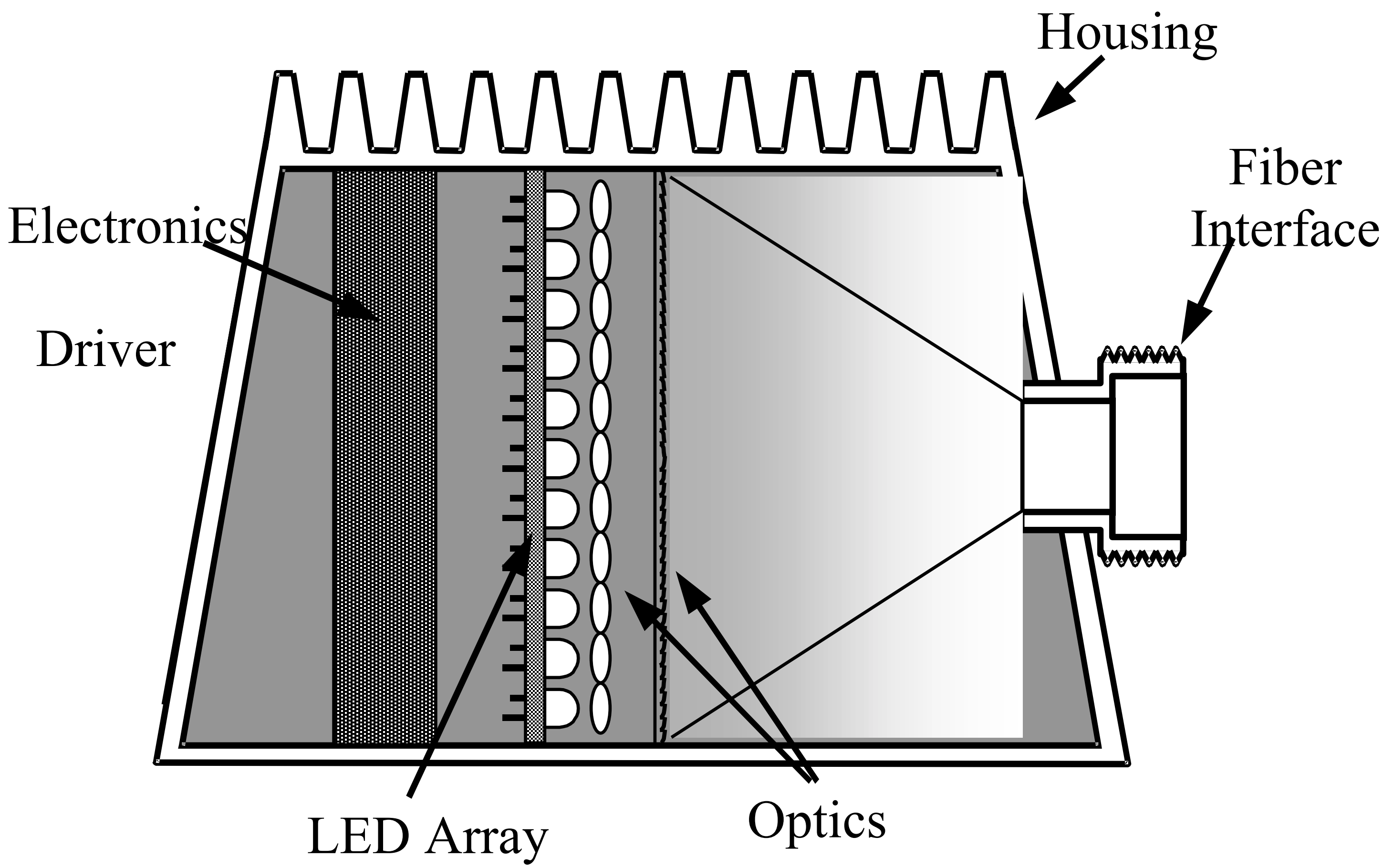
LED Applications - Lighting

- ILLUMINATION
  - Local Illumination
  - General Lighting



LED Floodlight (after A.García-Botella *et al., J. IES* **29**, 135, 2000)

Cross-section of a LED fiber light engine (after M. R. Krames *et al.*, P*roc. SPIE* **3938**, 2, 2000).



SOME of LED WEB SITES

- http://www.misty.com/people/don/led.html
- http://www.luxeon.com/index.html
- http://ledmuseum.home.att.net/
- http://www.nichia.com/
- http://www.cree.com/
- http://www.s-et.com
- http://www.oida.org/
- http://safeco2.home.att.net/laser.htm

Conclusion

"… it is vital to know that the LED is an ultimate form of lamp, in principle and in practice, and that its development indeed can and will continue until all power levels and colors are realized."

HOLONYAK, N., JR. (2000), "Is the light emitting diode (LED) an ultimate lamp?" *Am. J. Phys.* **68** (9), pp. 864-866.