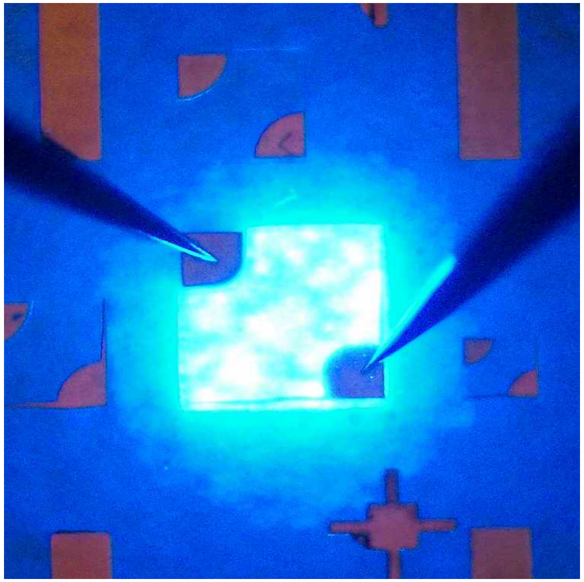
Optoelectronics
ELEC-E3210



Lecture 2

Light-emitting diodes

Outline

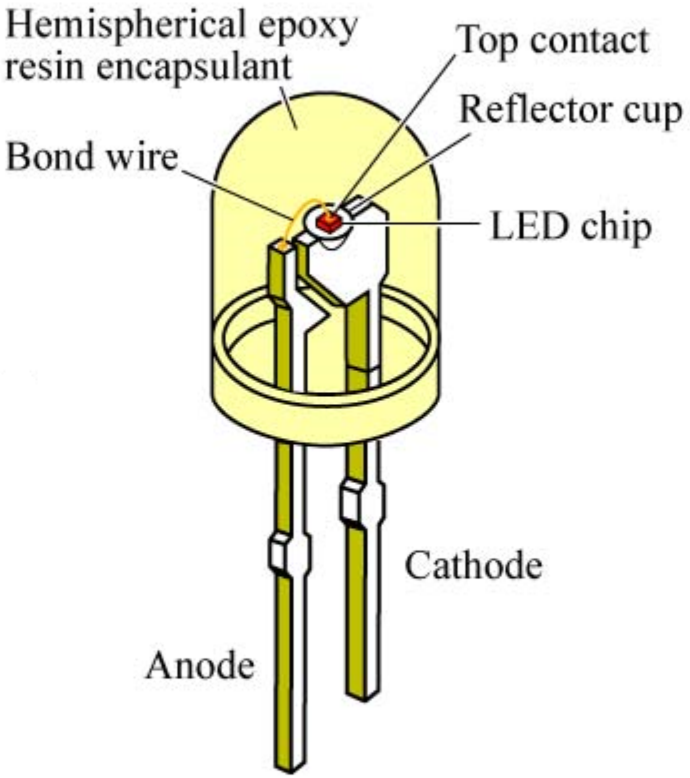
- 3 **LED structures**
- 4 **LEDs for telecommunication**
- 5 **LEDs for lighting/displays**

P. Bhattacharya: chapter 5
J. Singh: chapter 9

Hemispherical encapsulant

- Epoxy resin (n=1.4-1.7) is often used as encapsulant **to increase light extraction from the LED**

- The LED structure is placed in a tiny reflective cup so that the light from the active layer will be reflected toward the desired exit direction



Dome-shaped epoxy encapsulant

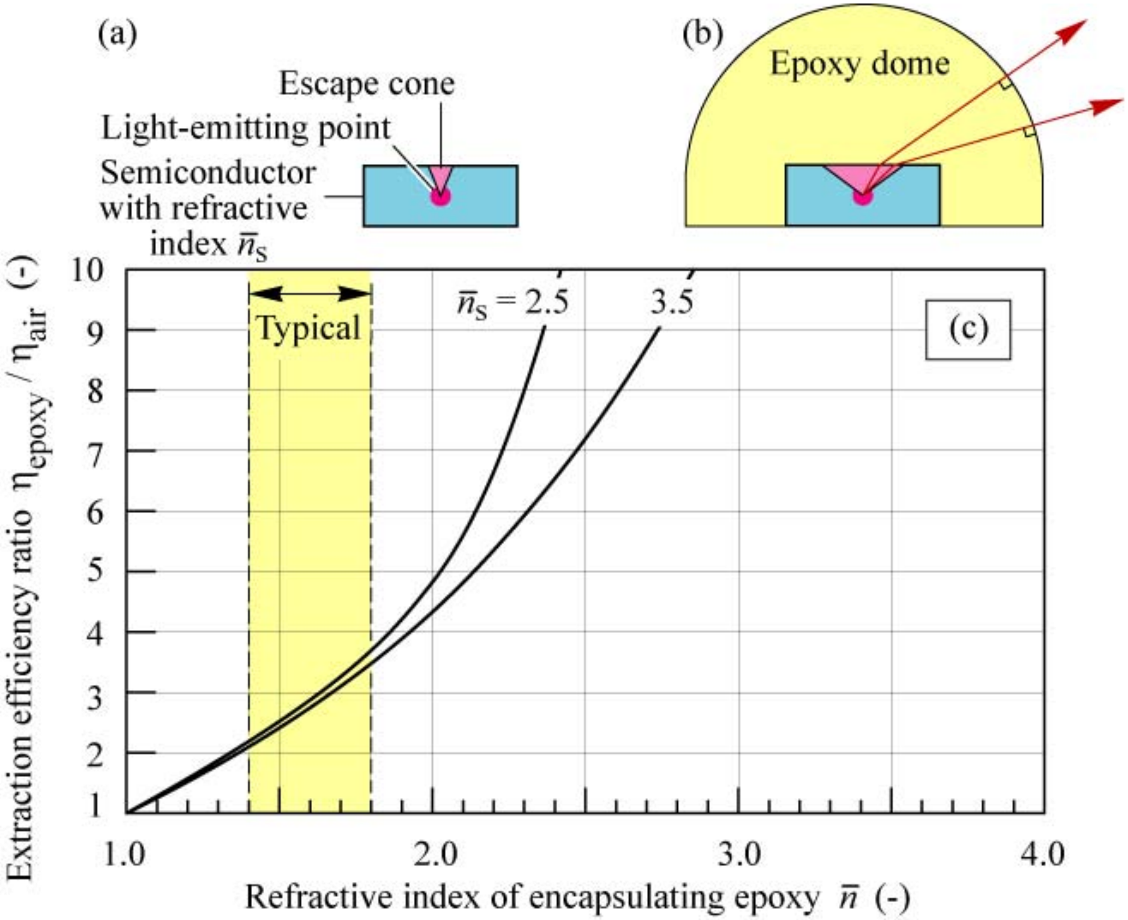


Fig. 5.6. (a) LED without and (b) with dome-shaped epoxy encapsulant. A larger escape angle is obtained for the LED with an epoxy dome. (c) Calculated ratio of light extraction efficiency emitted through the top surface of a planar LED with and without an epoxy dome. The refractive indices of typical epoxies range between 1.4 and 1.8 (adopted from Nuese *et al*., 1969).

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Epoxy increases extraction efficiency !

Die-shaped devices

Die-shape for enhanced light extraction

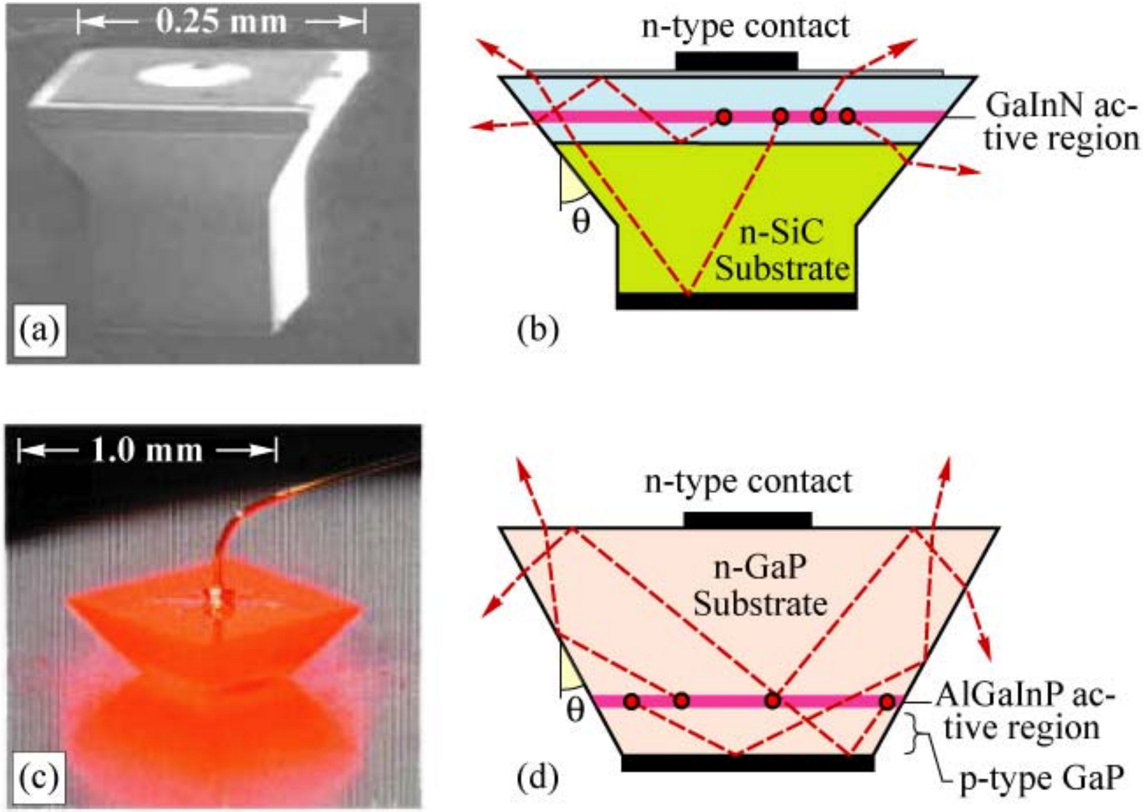

Fig. 9.6. Die-shaped devices: (a) Blue GaInN emitter on SiC substrate with trade name "Aton". (b) Schematic ray traces illustrating enhanced light extraction. (c) Micrograph of truncated inverted pyramid (TIP) AlGaInP/GaP LED. (d) Schematic diagram illustrating enhanced extraction (after Osram, 2001;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

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Truncated-inverted pyramid is one of the most efficienct LED designs but has an additional cost of die shaping.

Double heterostructure LED

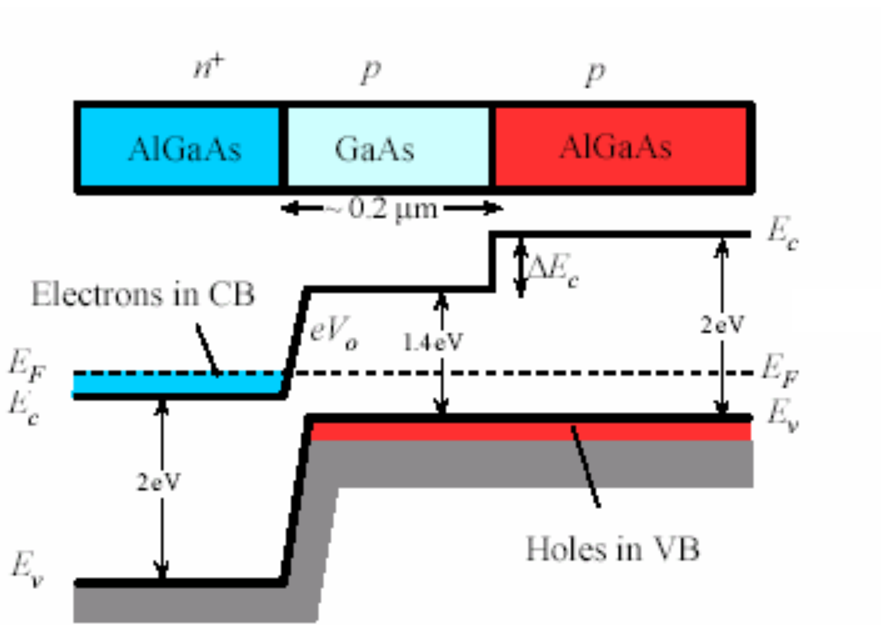
Homojunction LED has two main problems limiting η_{int} :

1. Surface states on the p-layer → nonradiative recombination

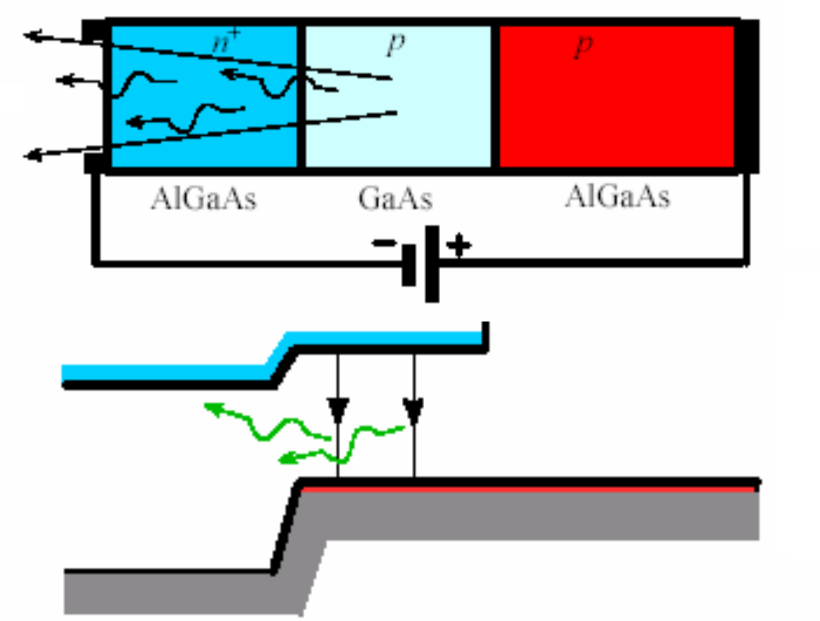
If the surface is far removed from the LED junction→ reabsorption

2. Photons are emerging from large effective volume (since the electrons can diffuse over long distances before recombining with holes)

These problems can be solved by using double heterostructure design!



No bias



Under forward bias

Current-spreading layer

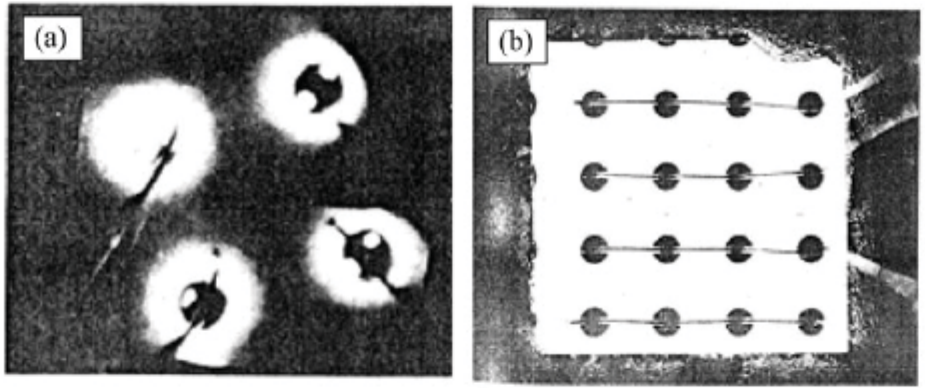
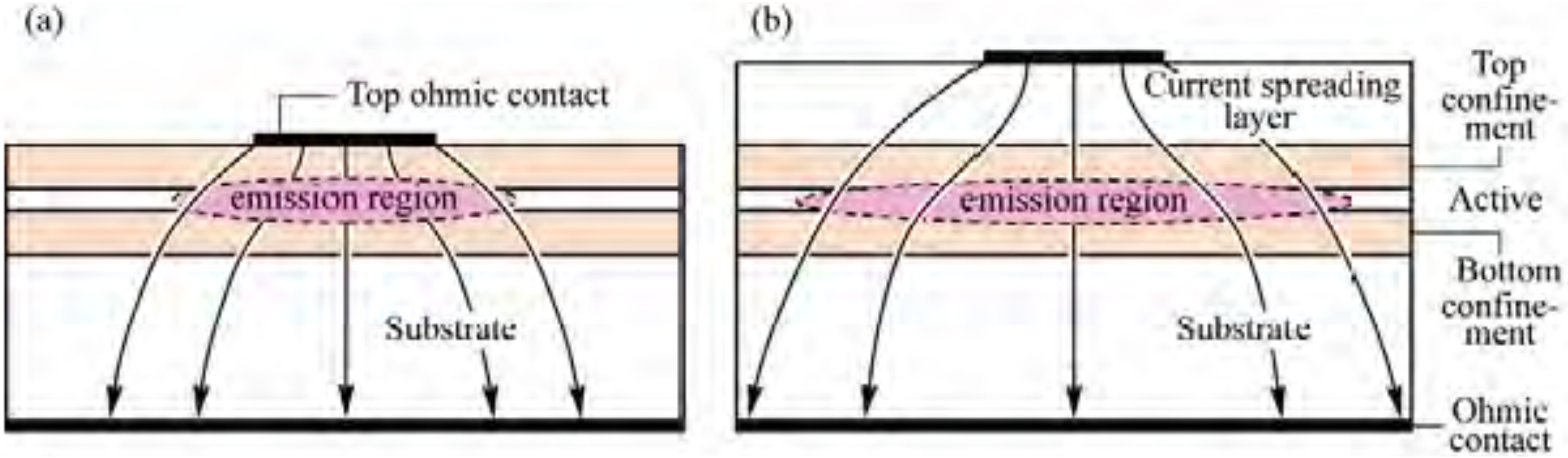
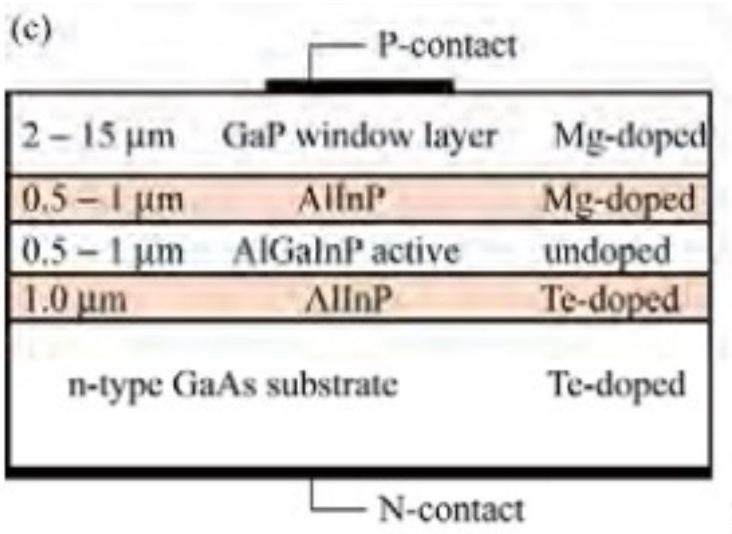


Fig. 8.1. Effect of the current-spreading layer on LED output. (a) Top view without a current-spreading layer. Emission occurs only near the perimeter of the contact. (b) Top view with a current-spreading layer (after Nuese *et al.*, 1969).

- Light is generated under top contact
- Top contact shadows light
- Current spreading layer spreads current to edges of the LED die



Current-spreading layer



Current-spreading layer = window layer

Depression in center due to top contact

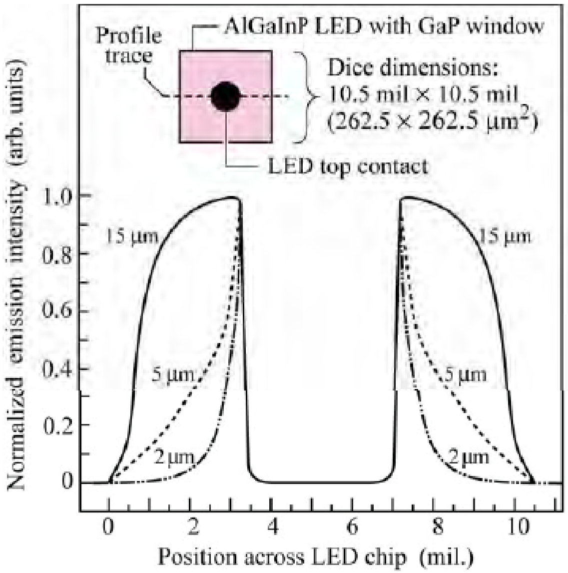
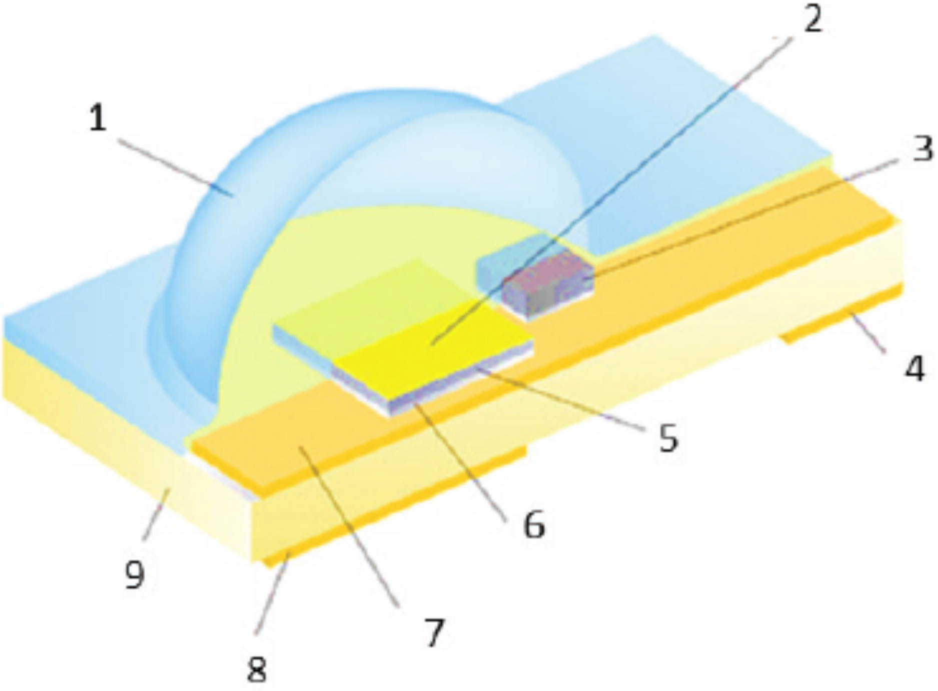


Fig. 8.3. The effect of GaP window thickness on current spreading is illustrated by surface light emission intensity profiles for three different AlGaInP LED chips with window layer thicknesses of 2, 5, and 15 µm. The profile is indicated by the dashed line in the inset. The dip in the middle of the profiles is due to the opaque ohmic contact pad. A microscope fitted with a video camara was used in the measurements (after Fletcher *et al.*, 1991a).

LED package design



1. Silicone Lens
2. Phosphor Plate
3. Transient Voltage Suppressor
4. Cathode
5. LED Chip
6. Bond Layer
7. Metal Interconnect Layer
8. Thermal Bed
9. Ceramic Substrate

Image Credit: Philips Lumileds

Besides the chip, various components are needed for thermal regulation, producing the desired spectrum, regulation electrical characteristics or creating the appropriate light distribution.

LED package design

Power packages provide

- Electrical path
- Optical path
- **Thermal path**

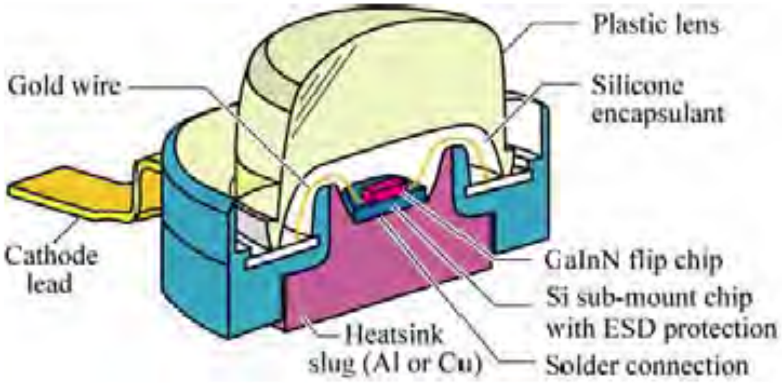
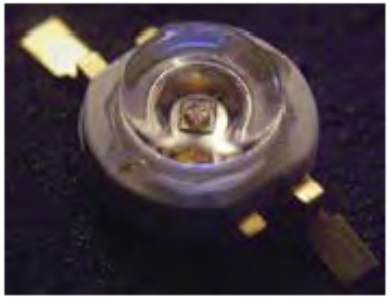


Fig. 11.2. Cross section through high-power package. The heatsink slug can be soldered to a printed circuit board for efficient heat removal. This package is called *Barracuda package* which was introduced by Lumileds Corp. (adopted from Krames, 2003).



Outline

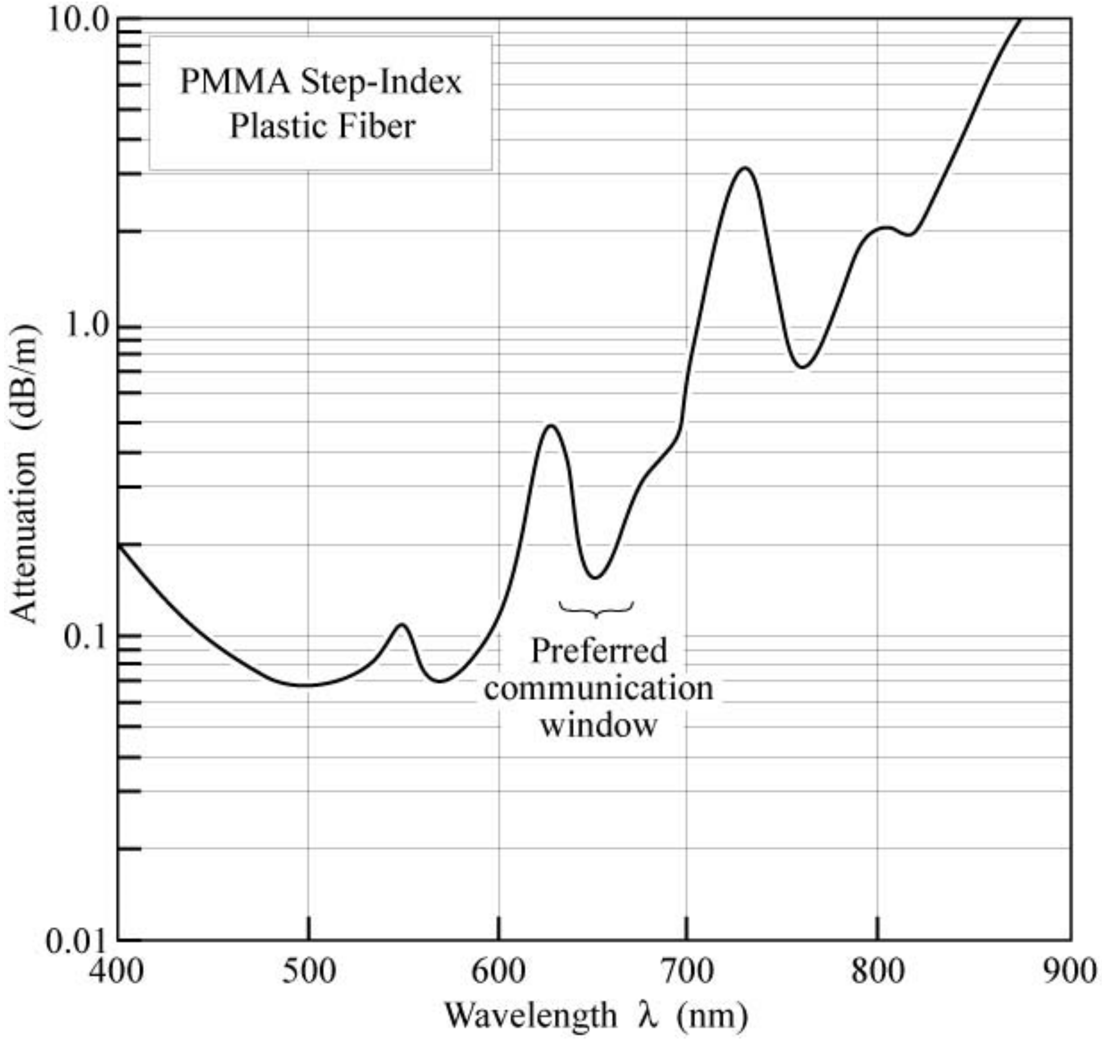
3 **LED structures**

4 **LEDs for telecommunication**

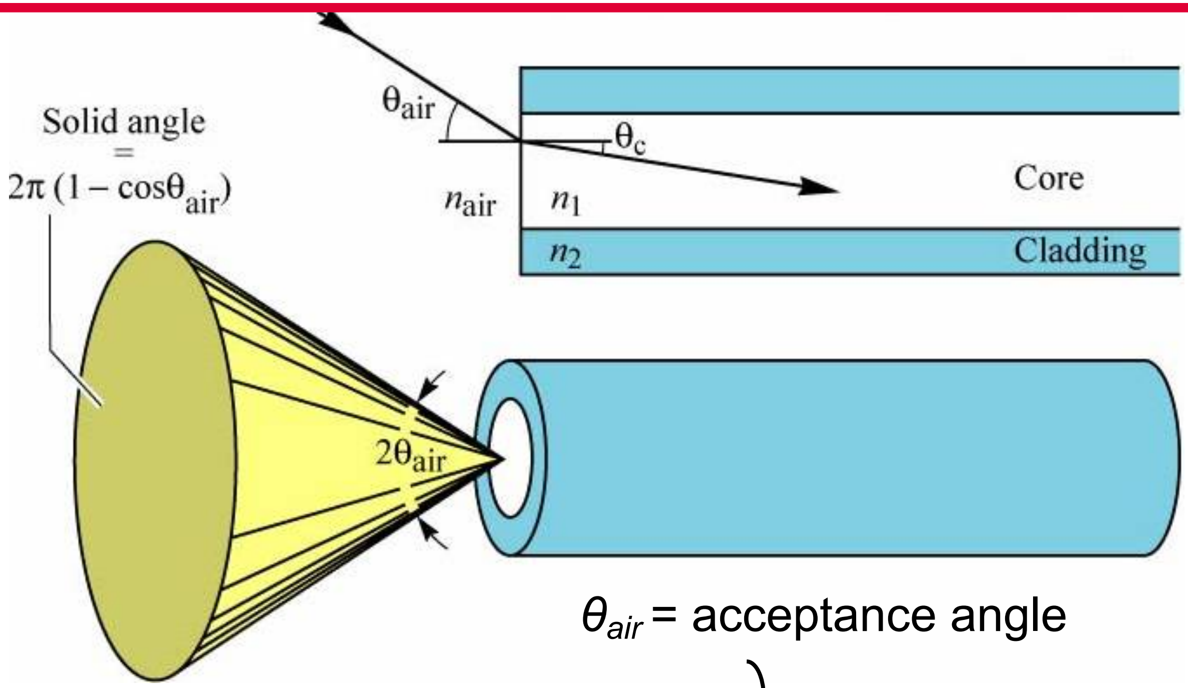
5 **LEDs for lighting/displays**

P. Bhattacharya: chapter 5
J. Singh: chapter 9

Attenuation in plastic fibers



Numerical aperture



θ_{air} = acceptance angle

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Critical angle: $\theta_c = \frac{\pi}{2} - \sin^{-1}\left(\frac{n_2}{n_1}\right)$

Numerical Aperture (NA) = $\sin\theta_{air}$

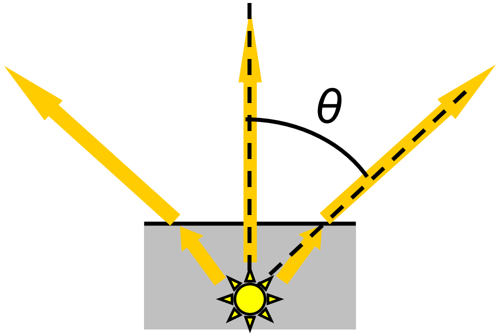
Snell law: $n_{air}\sin\theta_{air} = n_1\sin\theta_c$

$$NA = \sqrt{n_1^2 - n_2^2}$$

Coupling efficiency

We consider a Lambertian source from e.g. a planar LED put in close proximity to a fiber with numerical aperture NA. We suppose that the light source is punctual

$$I(\theta) = I_0 \cos(\theta)$$

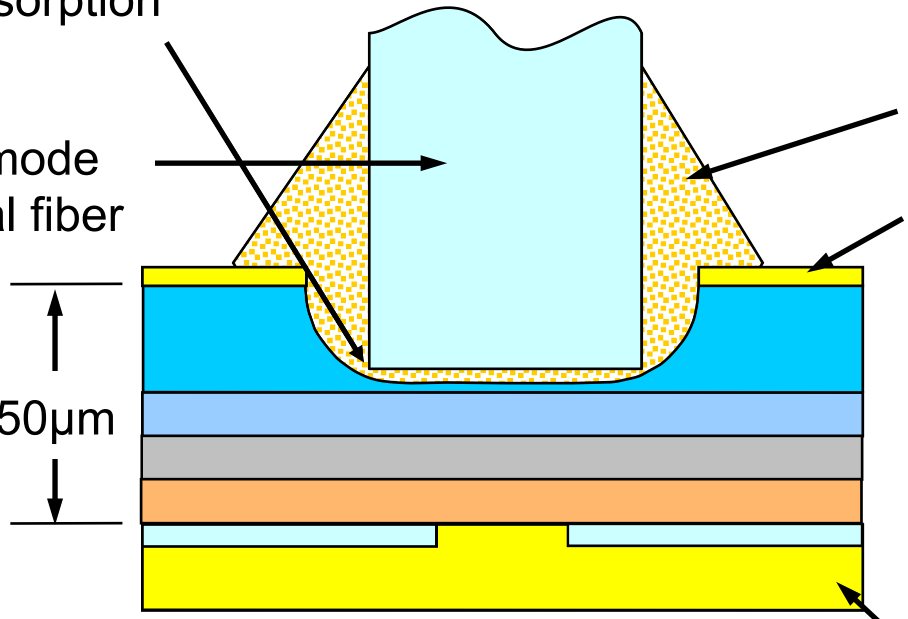


Planar LED

$$\eta_c = \frac{\int_0^{\theta_a} I_0 \sin(\theta) d\theta}{\int_0^{\pi/2} I_0 \sin(\theta) d\theta} = (NA)^2$$

Burrus-type LEDs

In the **Burrus-type LEDs**, the fiber is brought only a few mm away from the active region



Etched well to avoid reabsorption

Multimode optical fiber

Epoxy to held the butt-coupled fiber in place

Metal contact

n^+-GaAs, substrate

n-AlGaAs

GaAs, active layer

p-AlGaAs

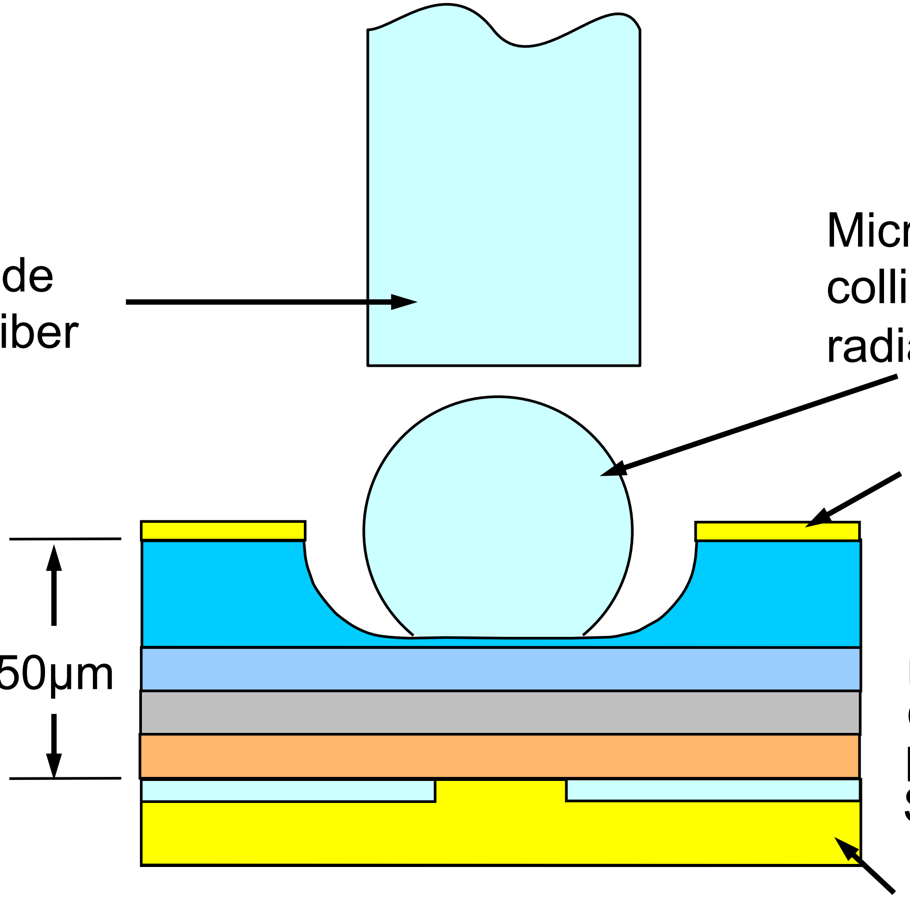
SiO_2 insulating layer

Metal contact

Coupling efficiency: 1-2%

→ Lambertian light source not ideal for fiber coupling

Microlens LEDs



Multimode optical fiber

Microlens ($TiO_2:SiO_2$) collimates the divergent radiation from LED

Metal contact

50μm

n^+-GaAs, substrate

n-AlGaAs

GaAs, active layer

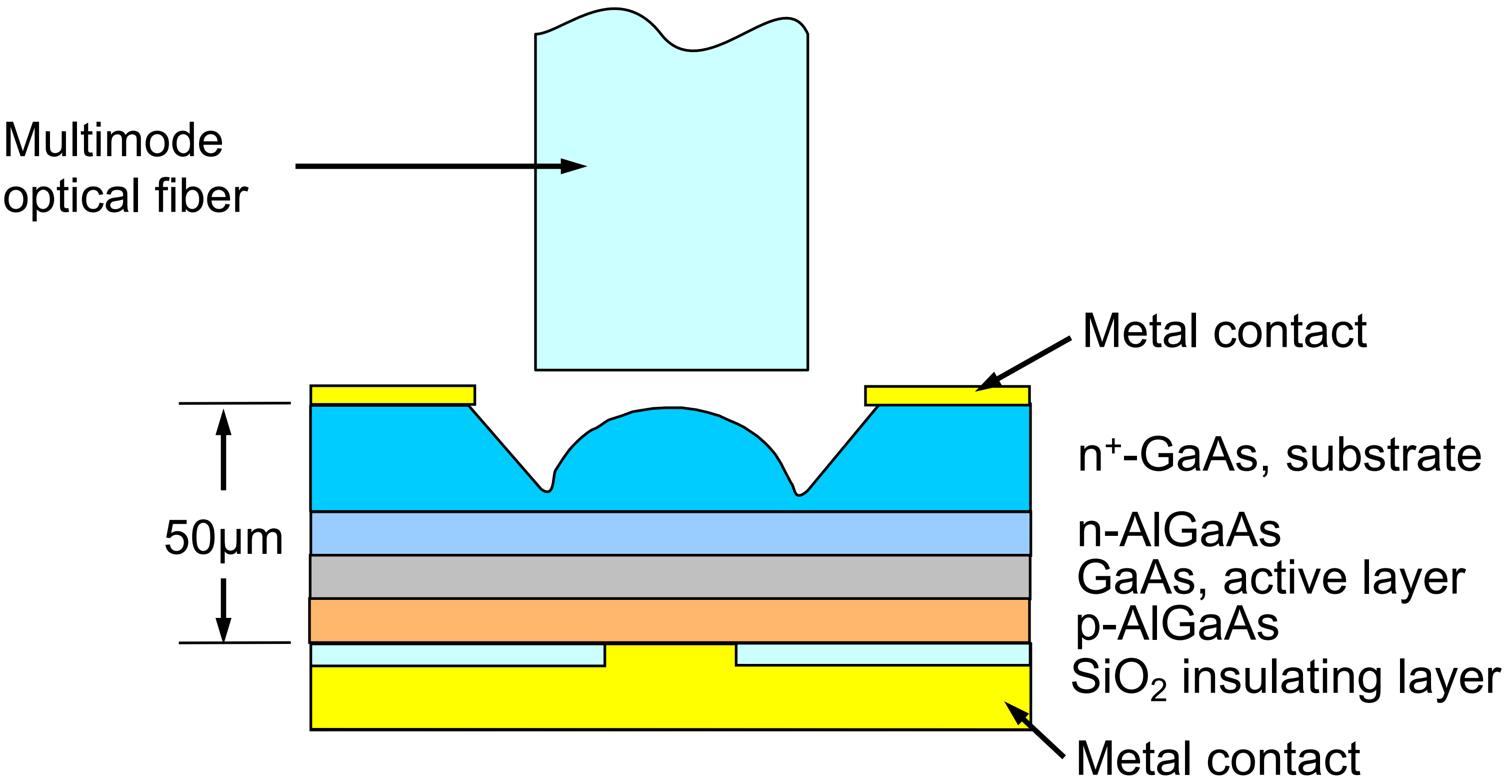
p-AlGaAs

SiO_2 insulating layer

Metal contact

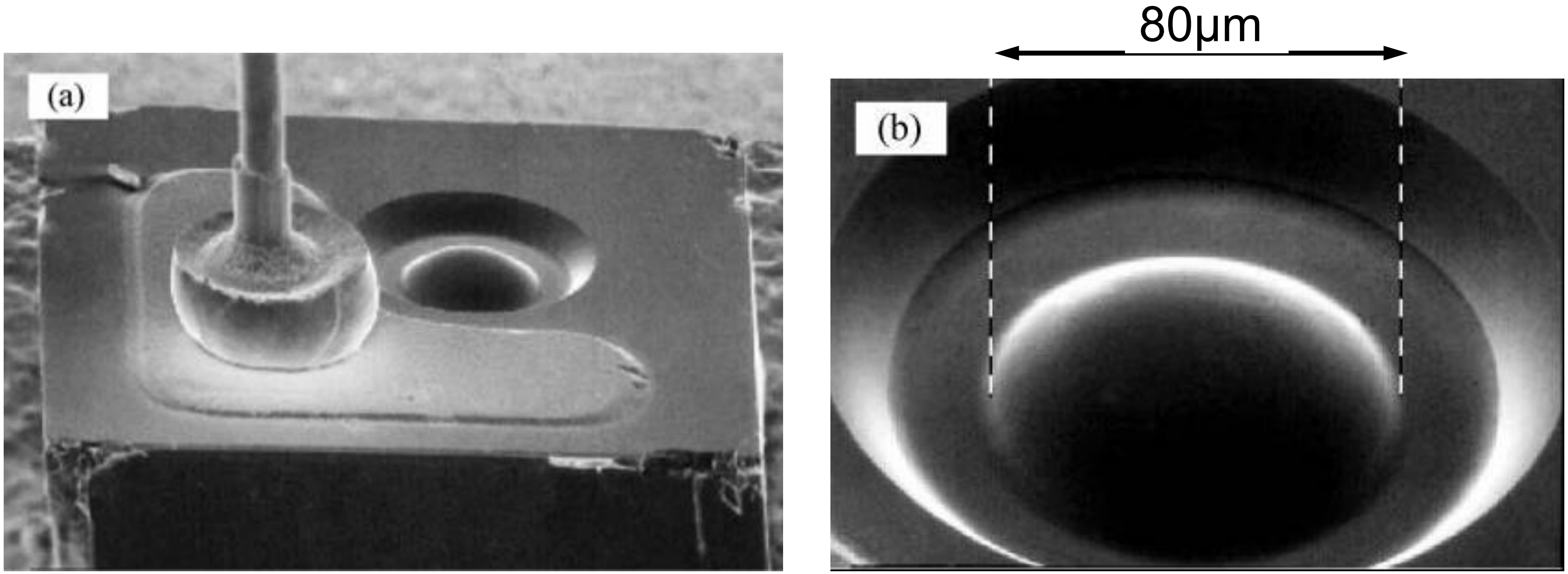
Coupling efficiency: up to 15%

LED with integrated lens



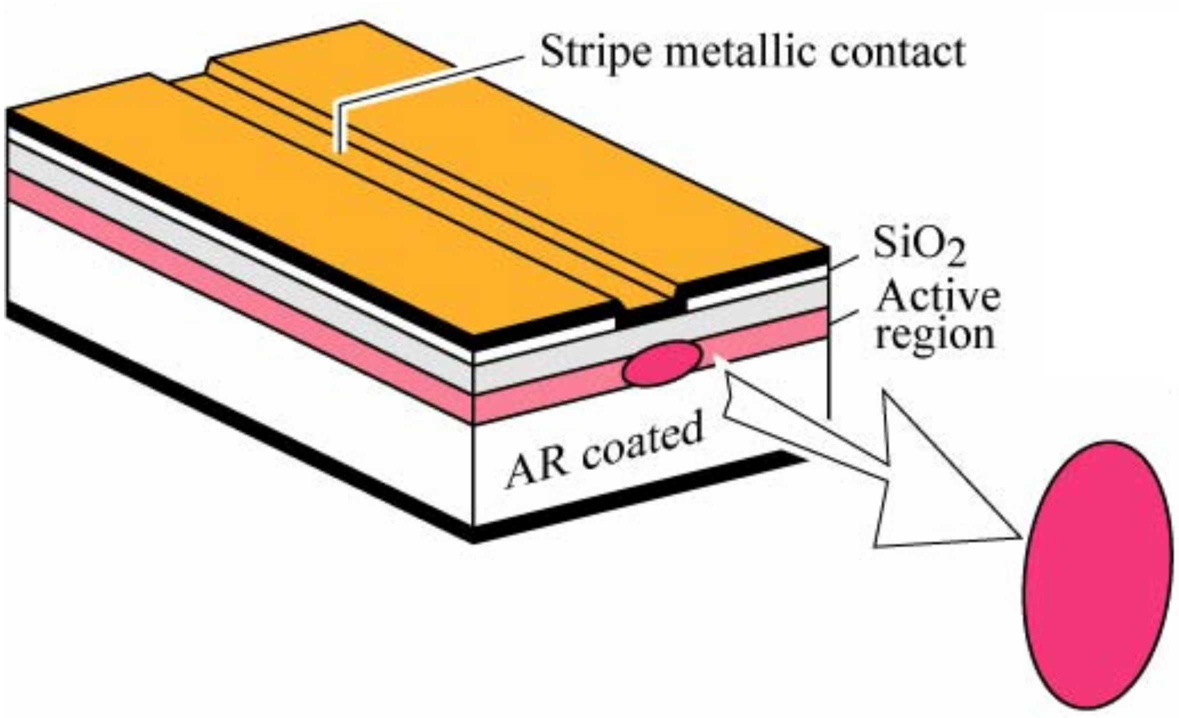
Coupling efficiency: up to 15%

LED with integrated lens



Despite problems with larger divergence and coupling of the beam, surface-emitting LEDs will remain important in large-volume, low-cost applications and for short-distance chip-to-chip communication.

Edge-emitting LEDs



In the edge emitter, the light is emitted in a relatively direct beam resulting in improved coupling into smaller fibers with an output similar to a laser

AlGaInP/GaAs LEDs for plastic optical fiber communications

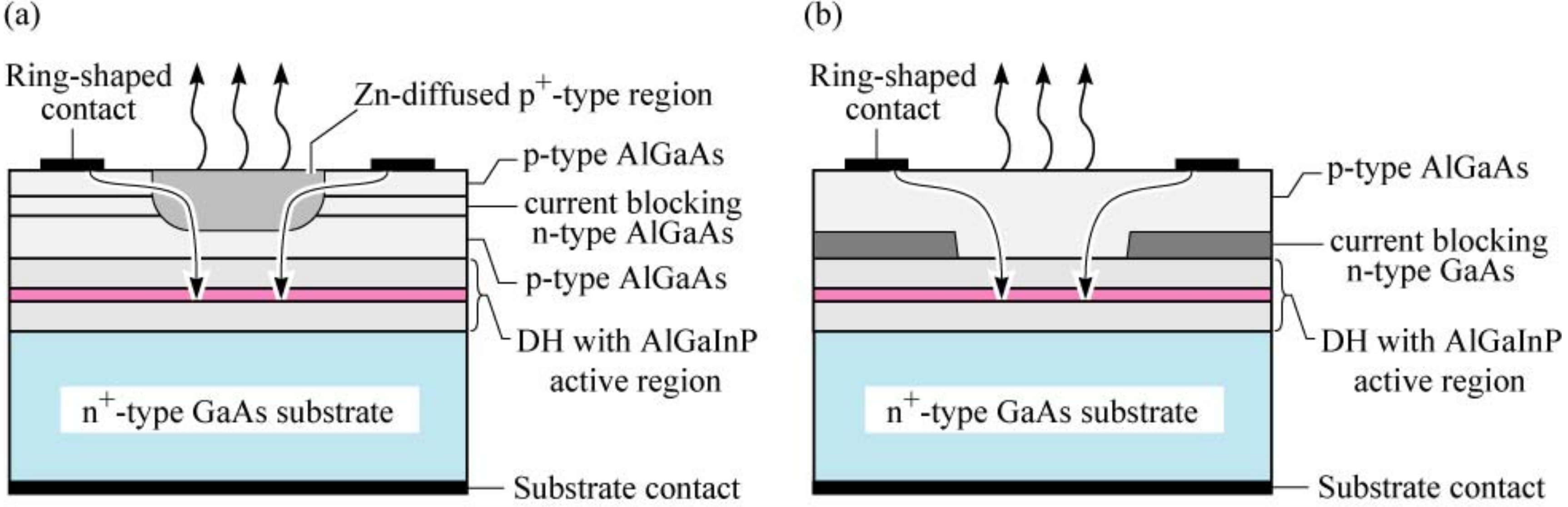


Fig. 23.5. AlGaInP/GaAs LED structures emitting at 650 nm for plastic optical fiber communications. Both LED structures funnel the current to the center of the active region where the emitted light is not obstructed by the top metal contact ring. (a) Structure using an n-type AlGaAs current blocking layer and a p$^+$-type diffusion region. (b) Structure fabricated by epitaxial regrowth using an n-type GaAs current blocking layer.

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InGaAsP/InP LED for 1300 nm

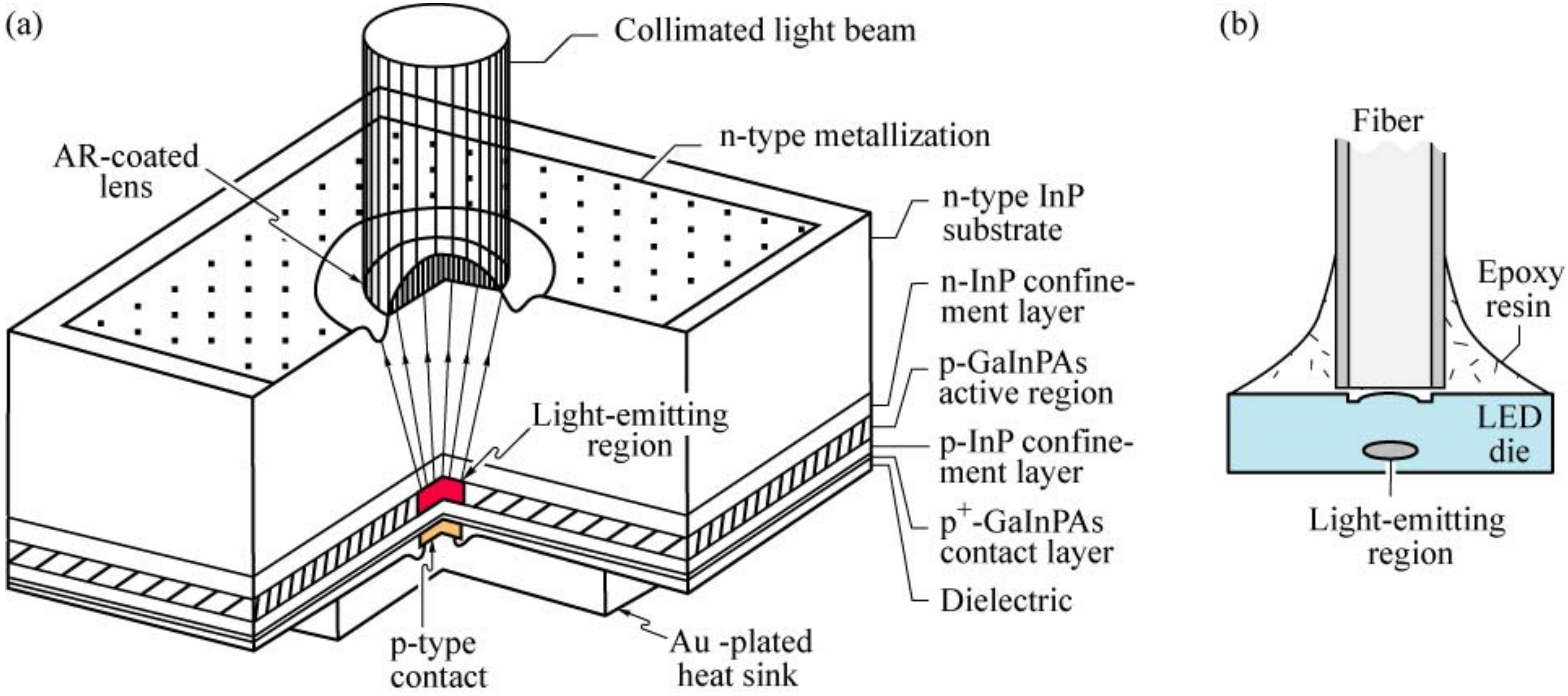

Fig. 23.2. (a) Structure of a communication LED emitting at 1300 nm with a GaInPAs active region lattice-matched to InP. The light generated in the active region is transmitted through the transparent InP substrate. The lateral dimension of the light-emitting region is defined by current injection under the circular ohmic contact with a diameter of 20 µm. An anti-reflection-coated (AR) lens, etched into the substrate, collimates the light beam. (b)Illustration of LED-to-fiber coupling using epoxy resin.

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Resonance Cavity LED (RCLED)

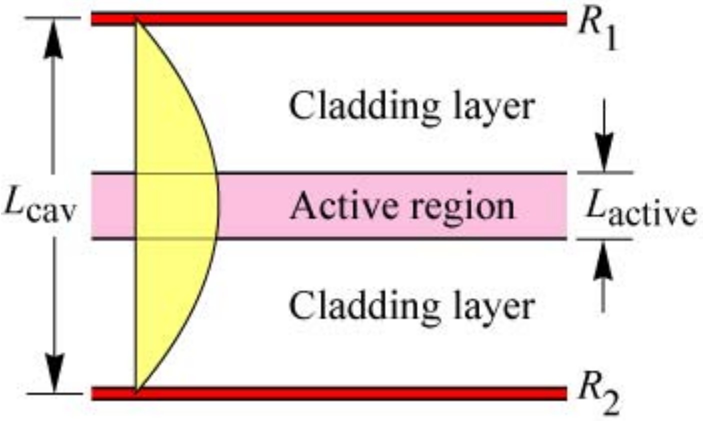

Fig. 15.1. Schematic illustration of a resonant cavity consisting of two metal mirrors with reflectivity R_1 and R_2. The active region has a thickness L_{active} and an absorption coefficient α. Also shown is the standing optical wave. The cavity length is L_{cav} is equal to $\lambda/2$.

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- Insert a light-emitting active region into an optical microcavity → optical mode density changes
- Resonant cavity: mode density has maximum at emission wavelength
- Enhanced spontaneous emission

RCLED cavity modes

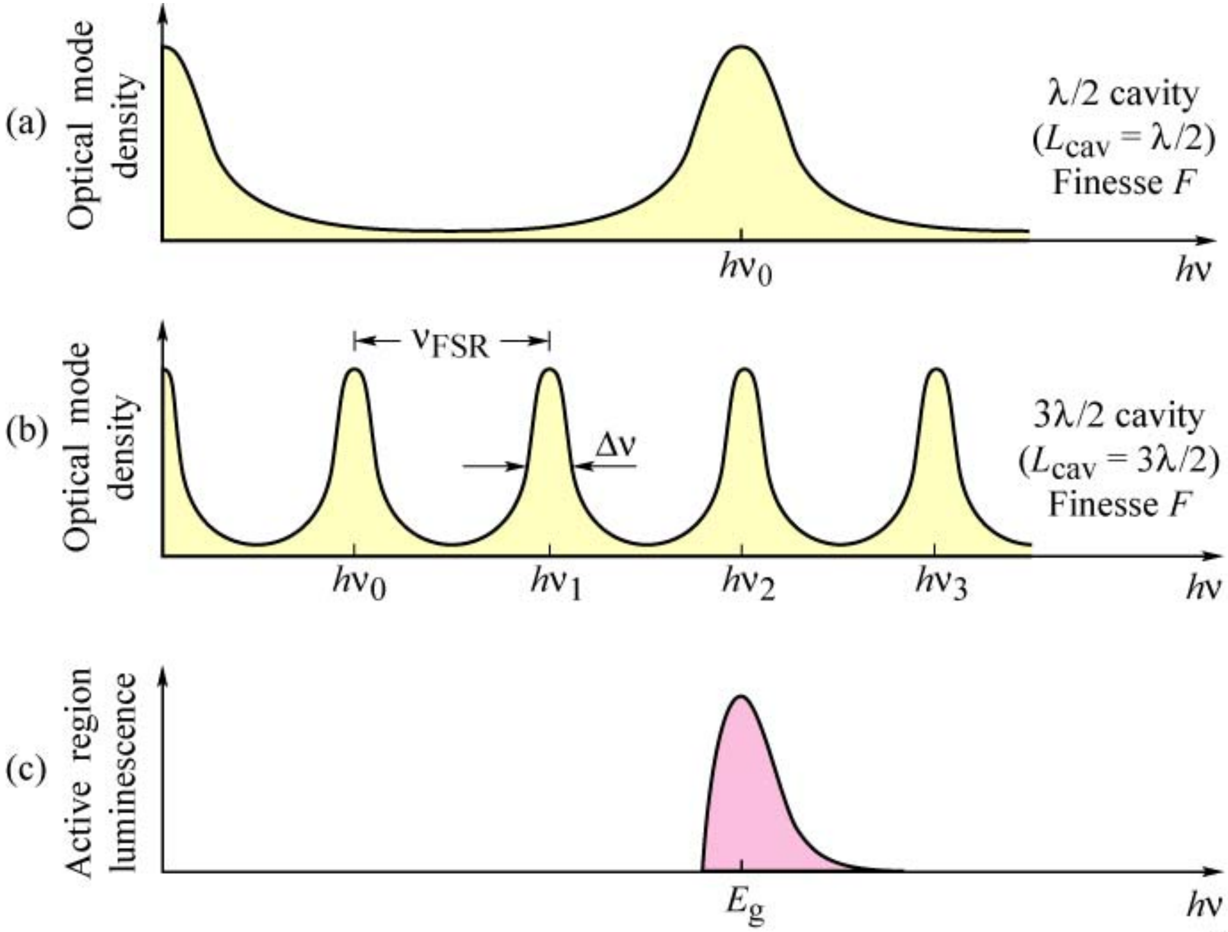

Fig. 15.2. Optical mode density for (a) a short and (b) a long cavity with the same finesse F. (c) Spontaneous free space emission spectrum of an LED active region. The spontaneous emission spectrum has a better overlap with the short-cavity mode spectrum compared with the long cavity mode spectrum.

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- RCLEDs are designed to overlap the natural emission band with an optical mode

First RCLED

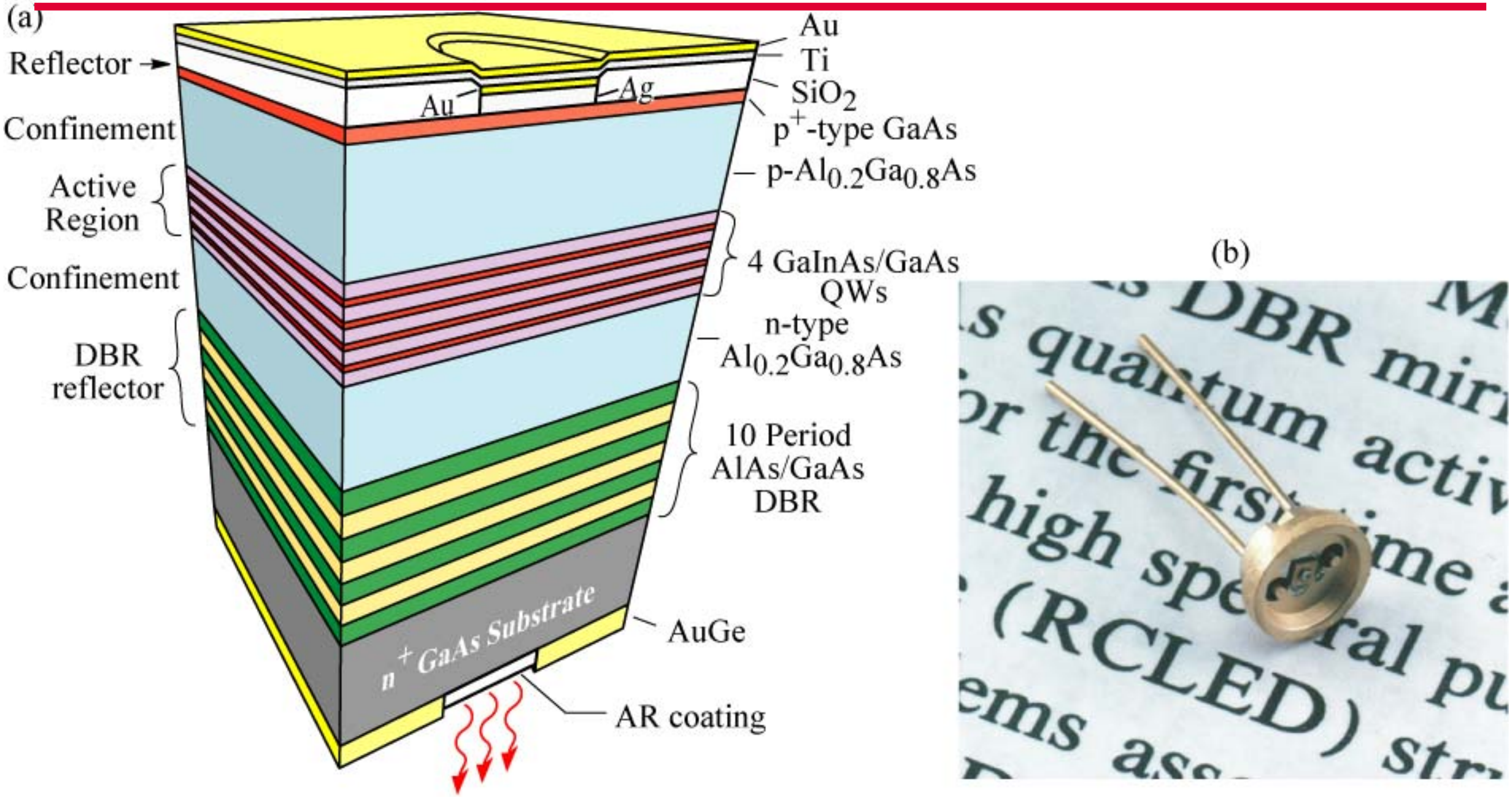

Fig. 15.4. (a) Schematic structure of a substrate-emitting GaInAs/GaAs RCLED consisting of a metal top reflector and a bottom distributed Bragg reflector (DBR). The RCLED emits at 930 nm. The reflectors are an AlAs/GaAs DBR and a Ag top reflector. (b) Picture of the first RCLED (after Schubert *et al*., 1994).

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RCLED emission spectrum

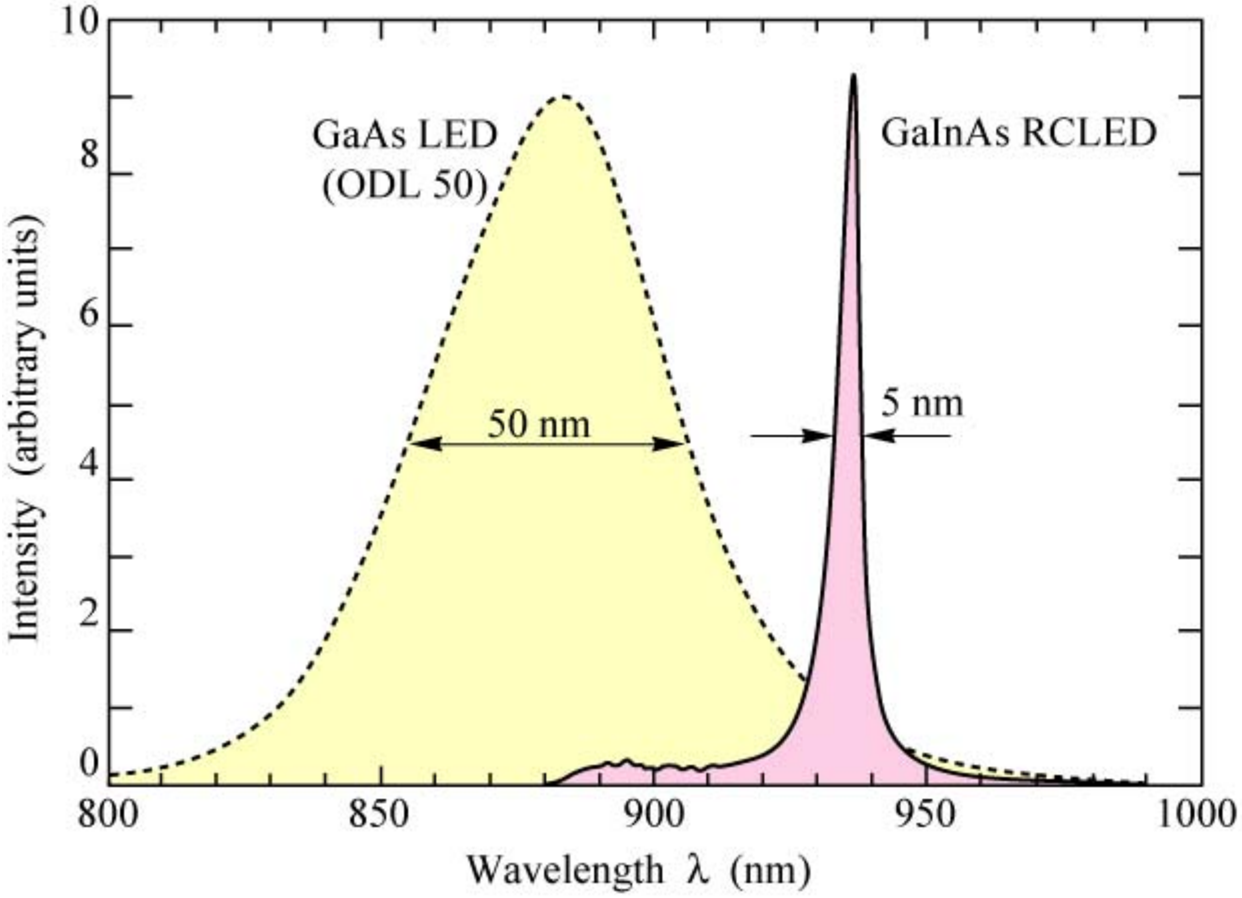

Fig. 15.6. Comparison of the emission spectra of a GaAs LED emitting at 870 nm (AT&T ODL 50 product) and a GaInAs RCLED emitting at 930 nm (after Hunt *et al*., 1993).

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- Narrow emission line

650 nm RCLED for communications

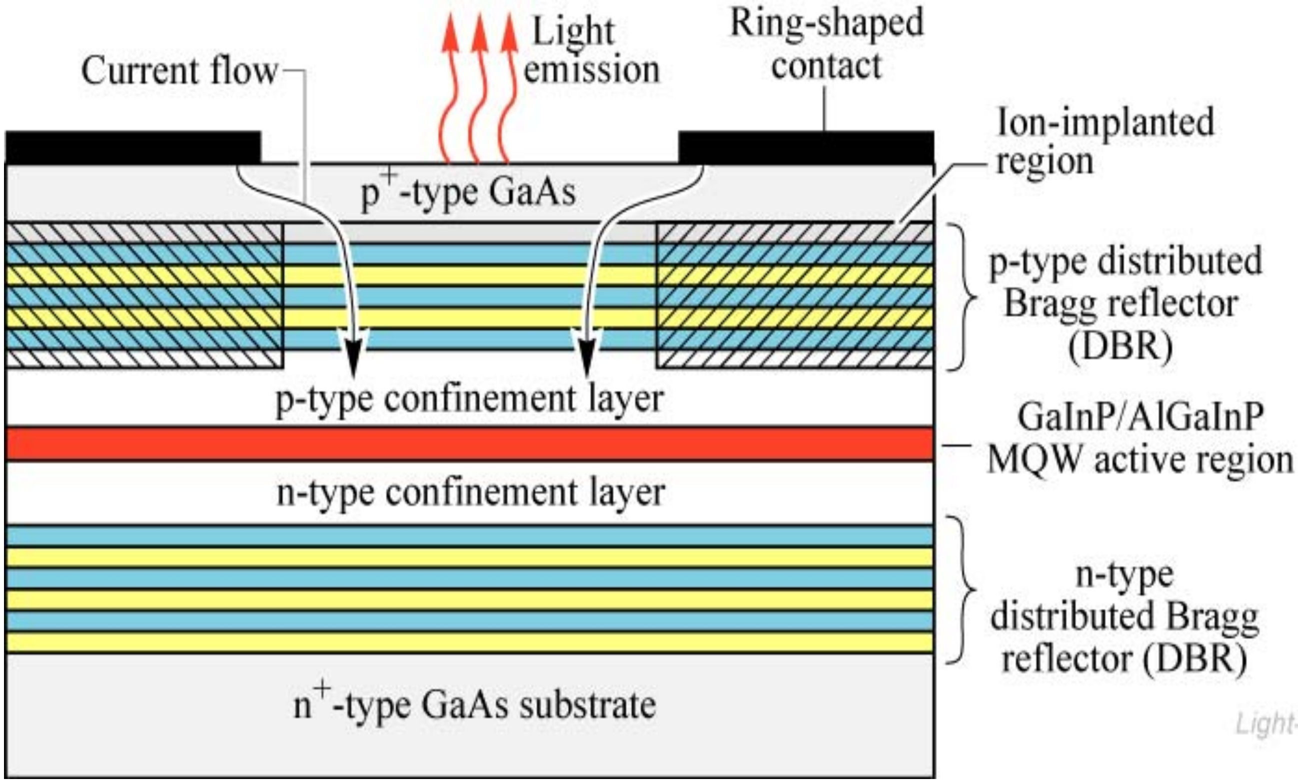

Fig. 15.9. Structure of a GaInP/AlGaInP/GaAs MQW RCLED emitting at 650 nm used for plastic optical fiber applications (after Whitaker, 1999)

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Outline

3 **LED structures**

4 **LEDs for telecommunication**

5 **LEDs for lighting/displays**

P. Bhattacharya: chapter 5
J. Singh: chapter 9

LED displays

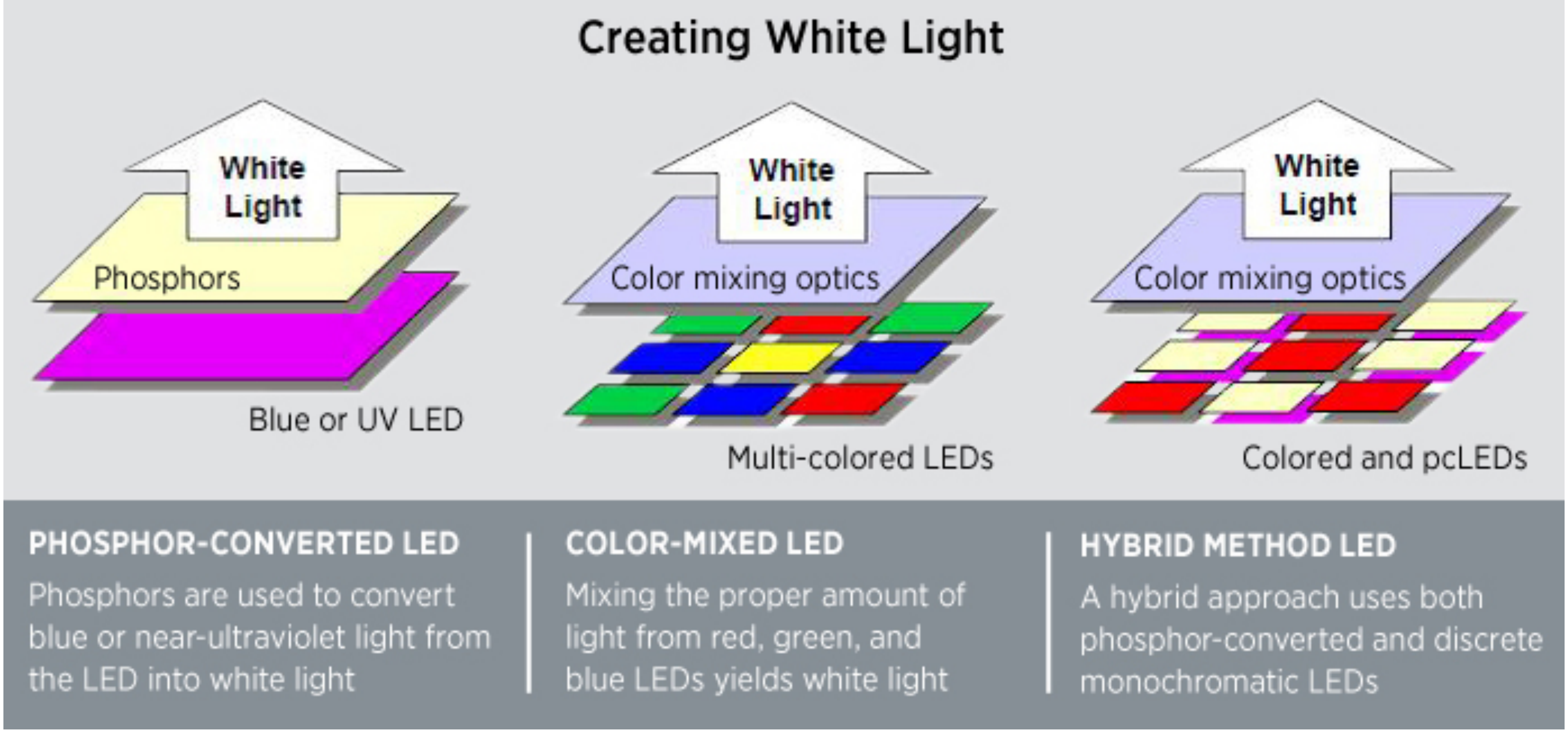
3 primary colors

Time square jumbo screen in New York made of 18 millions of LEDs

Advantages of LEDs for lighting

- LEDs can emit light of an intended color without the use of color filters
- Directional light emission
- Dimming and control capability
- Rapid on-off cycling capability without detrimental effects
- Resistance to mechanical failure (vibration etc. breaking)
- Extended lifetime
- Instant on at full output
- Size and form factor

White LEDs



PHOSPHOR-CONVERTED LED

Phosphors are used to convert blue or near-ultraviolet light from the LED into white light

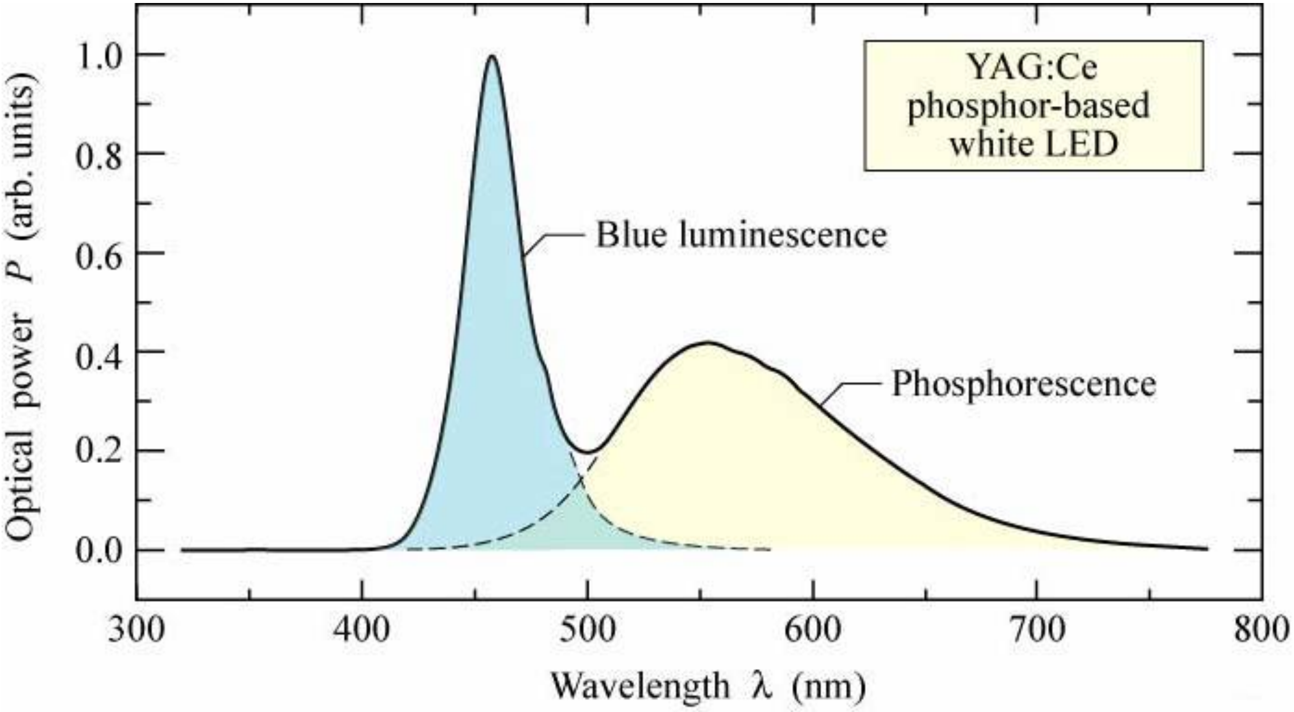
COLOR-MIXED LED

Mixing the proper amount of light from red, green, and blue LEDs yields white light

HYBRID METHOD LED

A hybrid approach uses both phosphor-converted and discrete monochromatic LEDs

Phosphor based white LEDs



Emission spectrum of a phosphor-based white LED manufactured by Nichia Corporation

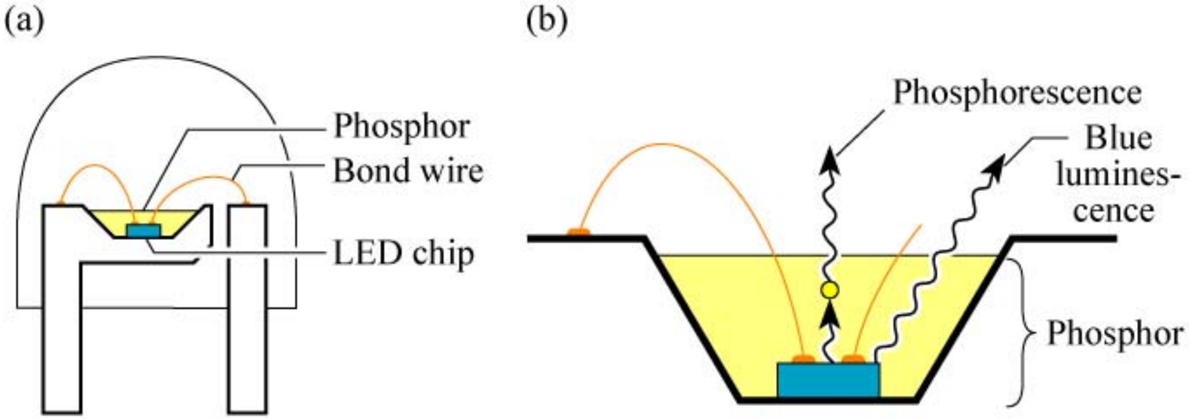


Fig. 21.7. (a) Structure of white LED consisting of a GaInN blue LED chip and a phosphor encapsulating the die. (b) Wavelength-converting phosphorescence and blue luminescence (after Nakamura and Fasol, 1997).

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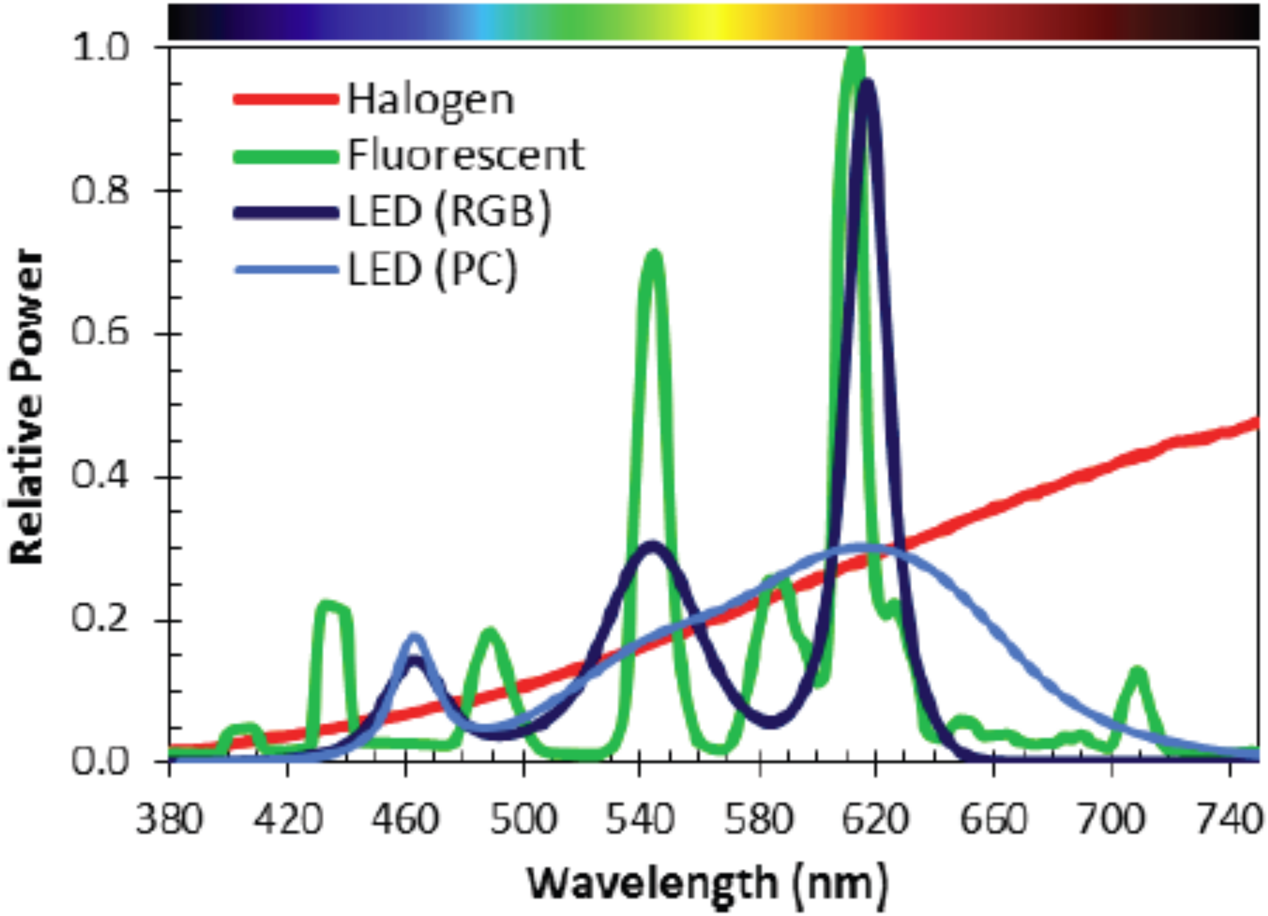


Figure 1. Due to the trichromatic nature of the human visual system, white light of equal appearance can be created with different spectral power distributions. This chart shows the spectral power distributions for four different light sources, all producing 2700 K white light with a CRI > 80.

Efficiency and Cost of White-Light Sources

Source efficacy (2012)

Incandescent	~15 lm/W
Halogen	~ 22 lm/W
Fluorescent	~ 60-120 lm/W
HID	~100-120 lm/W
LED white package	~100-140 lm/W
LED lamp	~70-90 lm/W

Long-term goal from US dept of Energy:

- 224 lm/W by 2025 in cost-effective market-ready systems

“Widespread use of LED lighting has the greatest potential impact on energy savings in the United States. By 2027, widespread use of LEDs could save about 348 TWh (compared to no LED use) of electricity: This is the equivalent annual electrical output of 44 large electric power plants (1000 megawatts each), and a total savings of more than $30 billion at today's electricity prices. “

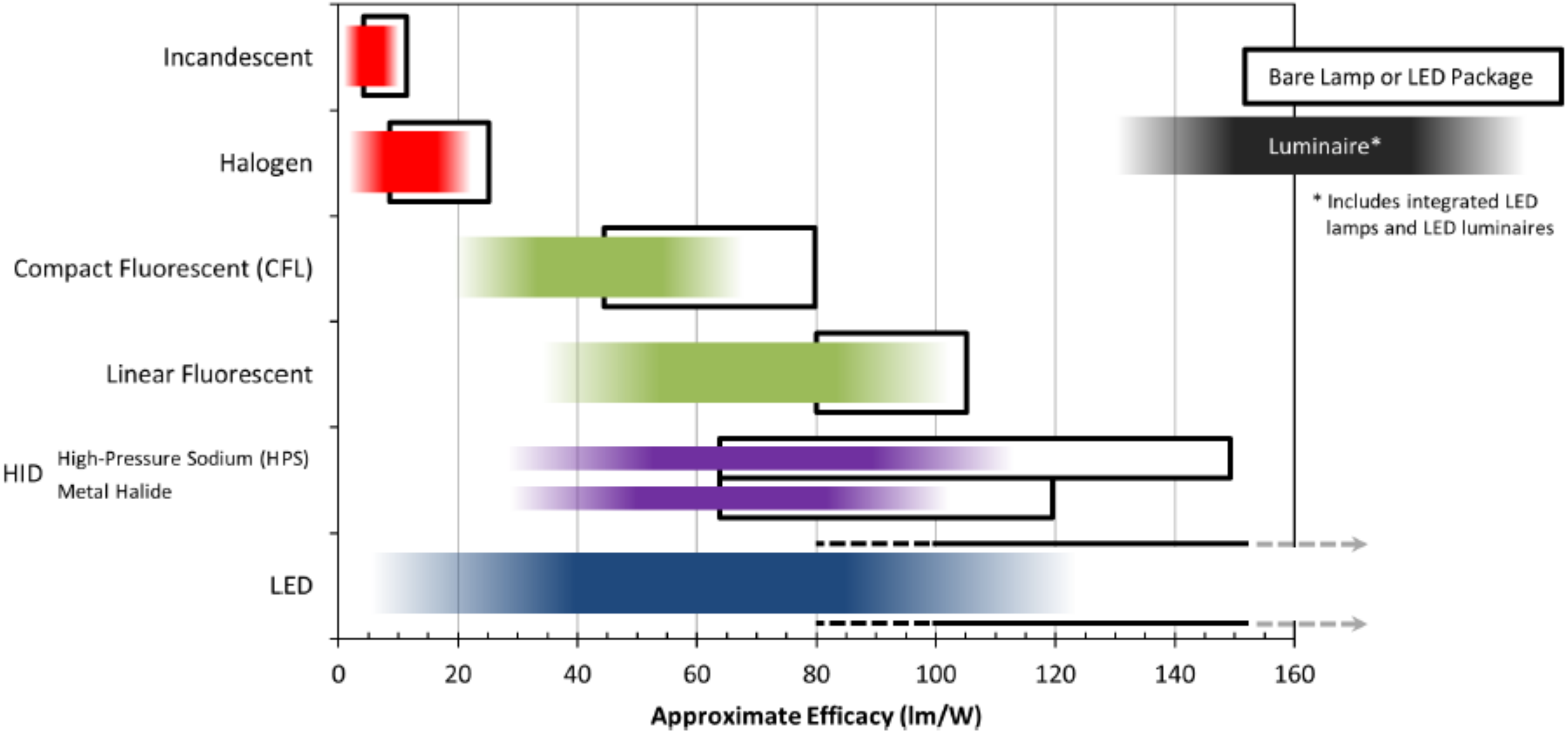
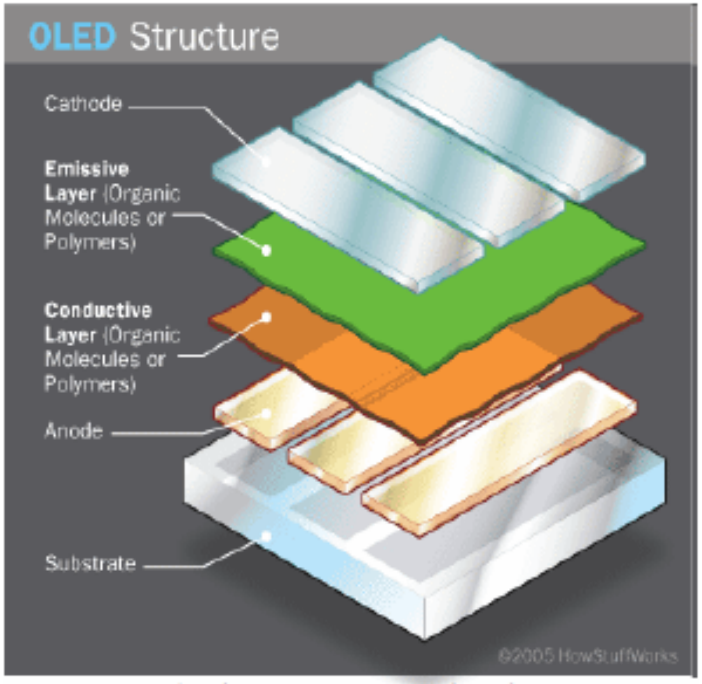
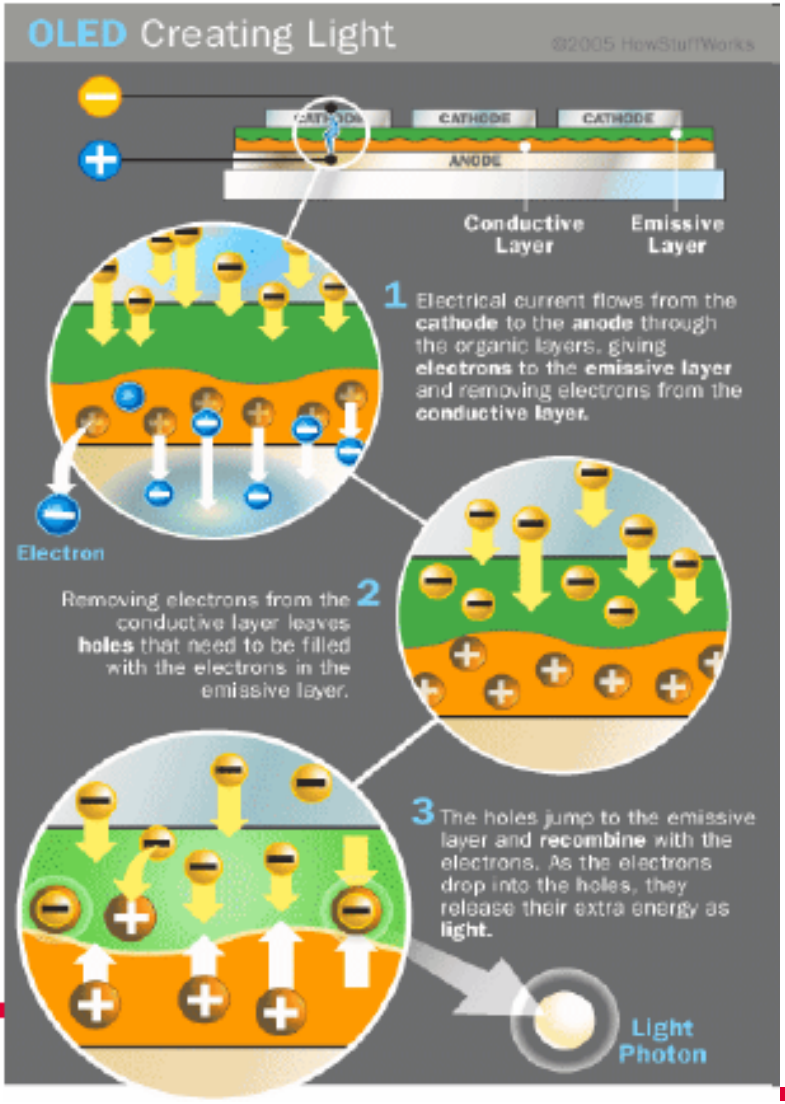


Figure 4. Approximate range of efficacy for various common light sources, as of January 2013. The black boxes show the efficacy of bare conventional lamps or LED packages, which can vary based on construction, materials, wattage, or other factors. The shaded regions show luminaire efficacy, which considers the entire system, including driver, thermal, and optical losses. Of the light source technologies listed, only LED is expected to make substantial increases in efficacy in the near future.

Organic and polymer LEDs



-in organic light emitting diode (OLED) electrons injected from cathode(-) recombine with holes injected from anode (+) at a single molecular site

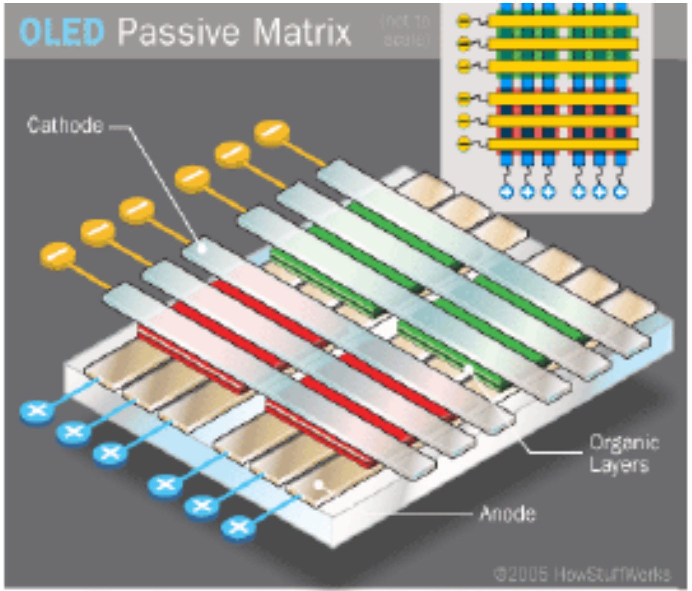


1 Electrical current flows from the **cathode** to the **anode** through the organic layers, giving **electrons** to the **emissive layer** and removing electrons from the **conductive layer.**

2 Removing electrons from the conductive layer leaves **holes** that need to be filled with the electrons in the emissive layer.

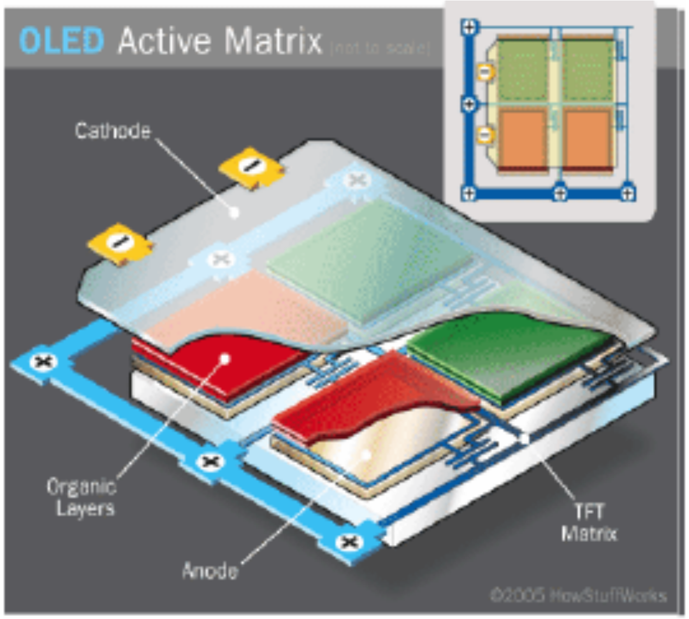
3 The holes jump to the emissive layer and **recombine** with the electrons. As the electrons drop into the holes, they release their extra energy as **light.**

Organic and polymer LEDs



Passive-matrix OLED (PMOLED)

PMOLEDs have strips of cathode, organic layers and strips of anode. The anode strips are arranged perpendicular to the cathode strips. The intersections of the cathode and anode make up the pixels where light is emitted. External circuitry applies current to selected strips of anode and cathode, determining which pixels get turned on and which pixels remain off. Again, the brightness of each pixel is proportional to the amount of applied current. PMOLEDs are most efficient for text and icons and are best suited for small screens (2- to 3-inch diagonal).



Active-matrix OLED (AMOLED)

AMOLEDs have full layers of cathode, organic molecules and anode, but the anode layer overlays a thin film transistor (TFT) array that forms a matrix. The TFT array itself is the circuitry that determines which pixels get turned on to form an image. The best uses for AMOLEDs are computer monitors, large-screen TVs and electronic signs or billboards.

Organic and polymer LEDs

- Advantages:
- -thinner, lighter, more flexible
- -can be printed onto any suitable substrate
- -flexibility enables new applications (displays embedded in fabrics or clothing, roll-up displays etc.)
- -greater range of colours, brightness, contrast, viewing angle than LCDs
- -fast response time
- -lower power consumption (no backlight needed)

- Disadvantages:
- -limited lifetime of organic materials (especially for blue light)
- -expensive manufacturing processes
- -careful sealing from water needed