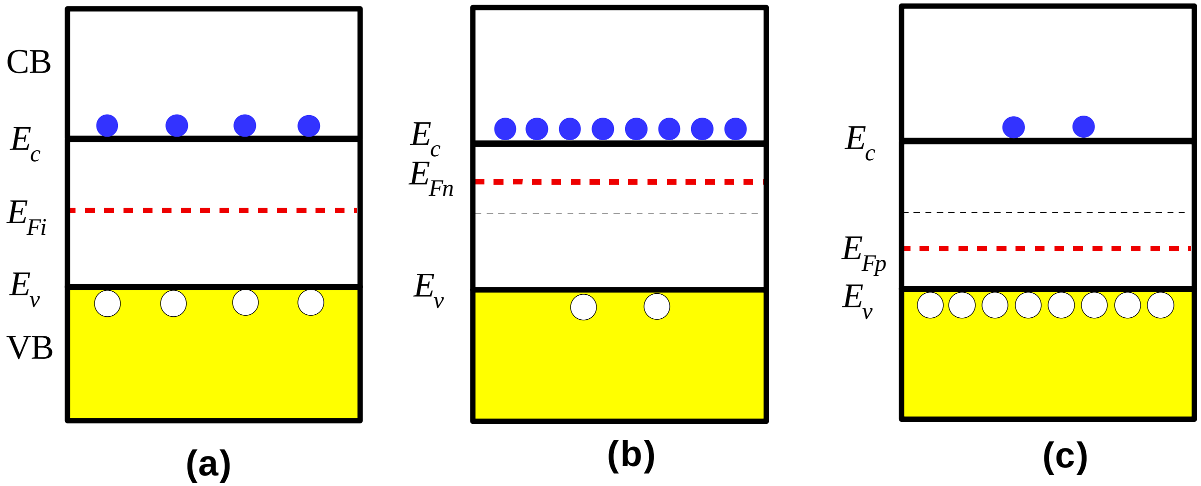
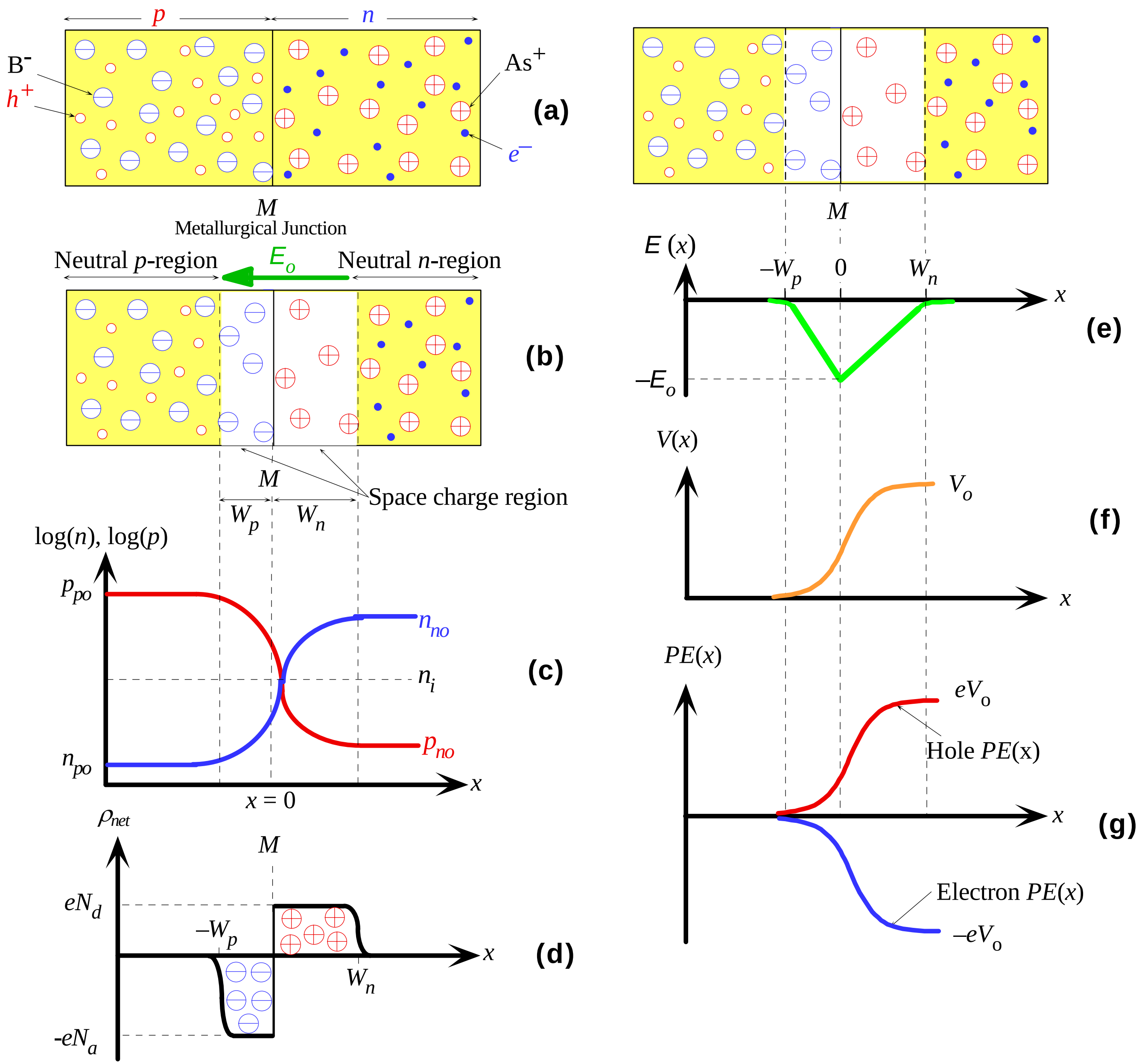


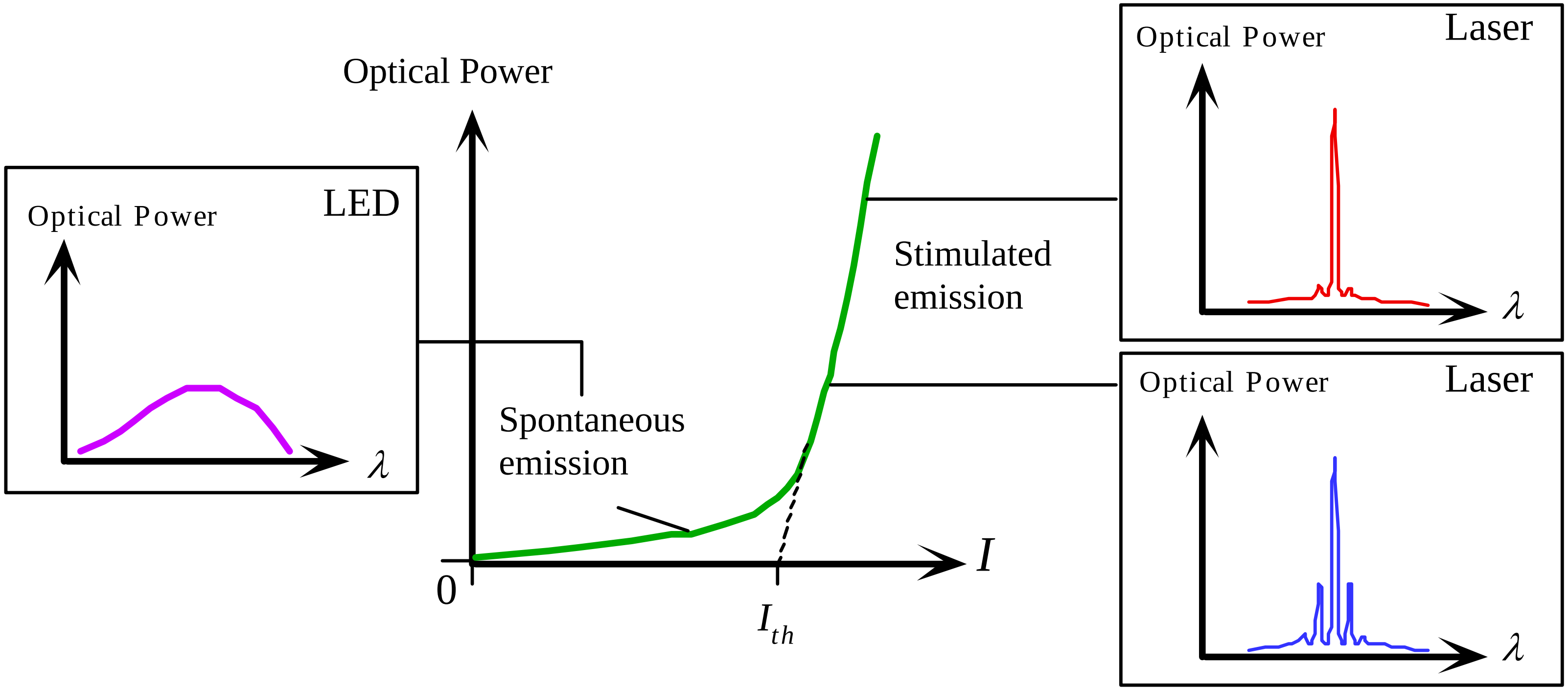
Energy band diagrams for (a) intrinsic (b) *n*-type and (c) *p*-type semiconductors. In all cases, $np = n_i^2$. Note that donor and acceptor energy levels are not shown.

Note that the holes in (b) are the minority carriers. Similarly for the electrons in (c)



Properties of the *pn* junction.

Light-Current Curve and Spectrum of an LD



Typical output optical power vs. diode current (I) characteristics and the corresponding output spectrum of a laser diode.

Efficiency and Power of an LED

The internal optical power is:

$$P_{\text{int}} = \eta_{\text{int}} \left(\hbar\omega / q\right) I$$

η_{int} is called the internal quantum efficiency, which is the fraction of electron-hole pairs that recombine radiatively, in this case generating spontaneous emission. η_{int} depends on the material quality. I is the injected current.

$$\eta_{\text{int}} = \frac{R_{rr}}{R_{tot}} = \frac{R_{rr}}{R_{nr} + R_{rr}} = \frac{\tau_{nr}}{\tau_{rr} + \tau_{nr}}$$

For direct bandgap semiconductors, the radiative and non-radiative lifetimes are comparable

$$R_{rr} = R_{spon} + R_{stim}$$

For LEDs, R_{stim} is negligible

Emitted Power in an LED

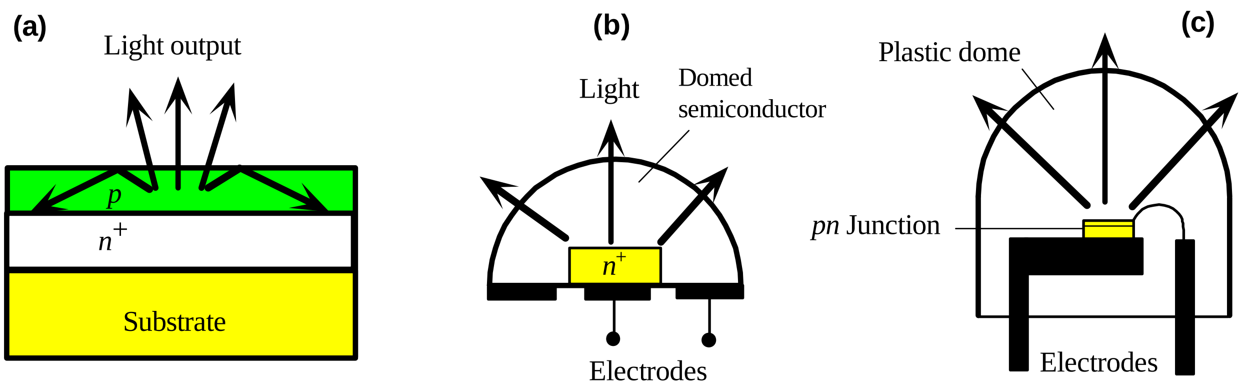
The emitted power must take into account the external quantum efficiency, η_{ext}, the fraction of photons that get out of the LED. Why is that an issue? TIR.

$$P_{ext} = \eta_{ext}\eta_{\text{int}}(\hbar\omega/q)I$$

Total Internal Reflection (TIR) in LEDs

LED efficiency is much lower than that of LDs? Why?

- spontaneous emission is slower than stimulated
- spontaneous emission is emitted in all directions



(a) Some light suffers total internal reflection and cannot escape. (b) Internal reflections can be reduced and hence more light can be collected by shaping the semiconductor into a dome so that the angles of incidence at the semiconductor-air surface are smaller than the critical angle. (b) An economic method of allowing more light to escape from the LED is to encapsulate it in a transparent plastic dome.

Equations for TIR-limited η_{ext} in an LED

The critical angle is:

$$\theta_c = \sin^{-1}(1/n)$$

Where *n* is the refractive index of the semiconductor, or about 3.5

Then the η_{ext} can be written as:

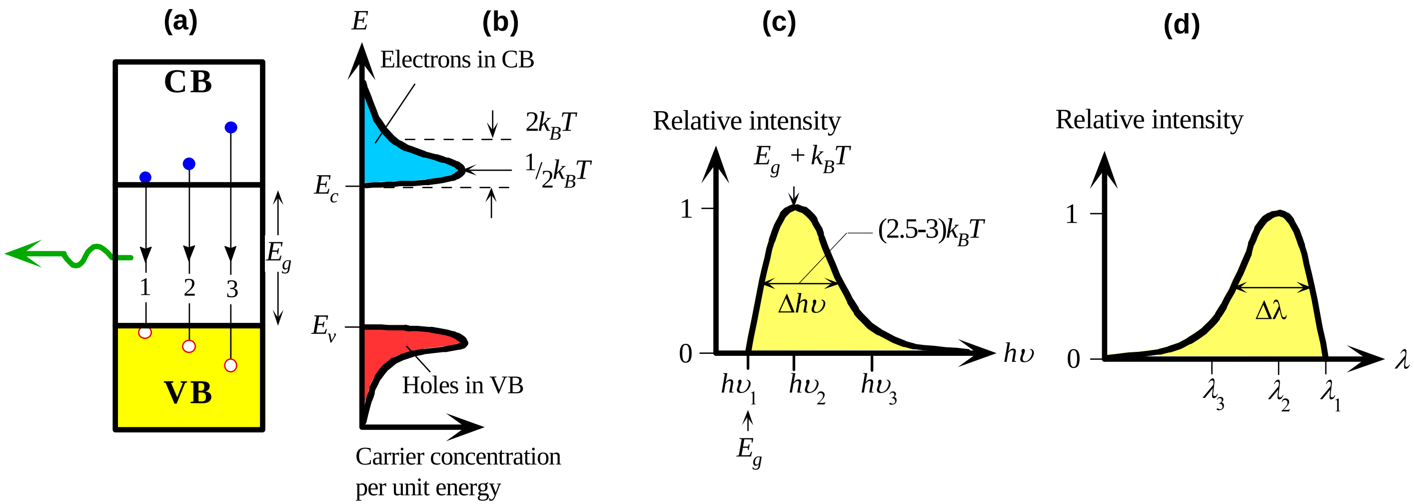
$$\eta_{ext} = \frac{1}{4\pi}\int_0^{\theta_c} T_f(\theta)(2\pi\sin\theta)\,d\theta$$

Assuming $T_f(\theta) = T_f(0) = 4n/(n+1)^2$, then

$$\eta_{ext} = n^{-1}(n+1)^{-2}$$

Which means $\eta_{ext} = 1.4\%$ when $n = 3.5$

The spectral linewidth of LEDs



(a) Energy band diagram with possible recombination paths. (b) Energy distribution of electrons in the CB and holes in the VB. The highest electron concentration is $(1/2)k_BT$ above E_c. (c) The relative light intensity as a function of photon energy based on (b). (d) Relative intensity as a function of wavelength in the output spectrum based on (b) and (c).

LED linewidth equation:

$$R_{spon}(\omega) = A_0\left(\hbar\omega - E_g\right)^{1/2}\exp\left[-\left(\hbar\omega - E_g\right)/k_BT\right]$$

$\Delta\lambda$ = 50-60 nm, so LEDs are suitable for 10-100 Mb/s over a few km

Modulation Response of LEDs

The rate equation: source term and recombination term:

$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_c}$$

N is the carrier density (cm^{-3}), V is the volume of active region (where the recombination occurs) and τ_c is the carrier lifetime

Another way of looking at it: $N/\tau_c = R_{spon} + R_{nr}$

Now introduce a small-signal sinusoidal modulation to the bias current

$$I(t) = I_b + I_m \exp(i\omega_m t)$$

And the carrier density, N, also has a similar general solution (see next page)

Modulation Response of the LED continued

$$N(t) = N_b + N_m \exp(i\omega_m t)$$

General solution for the carrier density ($N = P$)

where $N_b = \dfrac{\tau_c I_b}{qV}$

Steady-state carrier density

$$N_m(\omega_m) = \frac{\tau_c I_m / qV}{1 + i\omega_m \tau_c}$$

The small signal response of the carrier density

The modulated power, P_m, which we are interested in, is linear with $|N_m|$ there is one photon out for one electron-hole pair in.

LED transfer function, $H(\omega_m)$

$$H(\omega_m) = \frac{N_m(\omega_m)}{N_m(0)} = \frac{1}{1 + i\omega_m \tau_c}$$

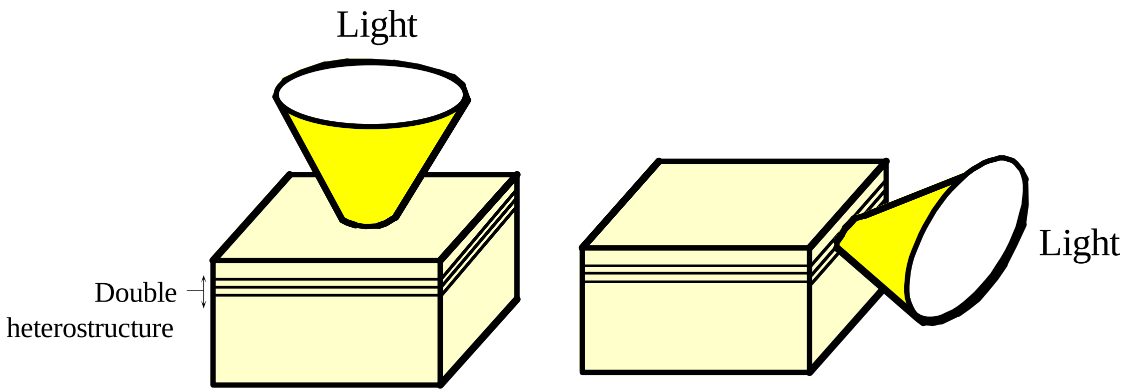
This is an optical power transfer function

$$f_{3dB} = \frac{\sqrt{3}}{2\pi\tau_c}$$

This is the 3-dB **optical** bandwidth of an LED. The 3-dB electrical bandwidth is $1/2\pi\tau_c$

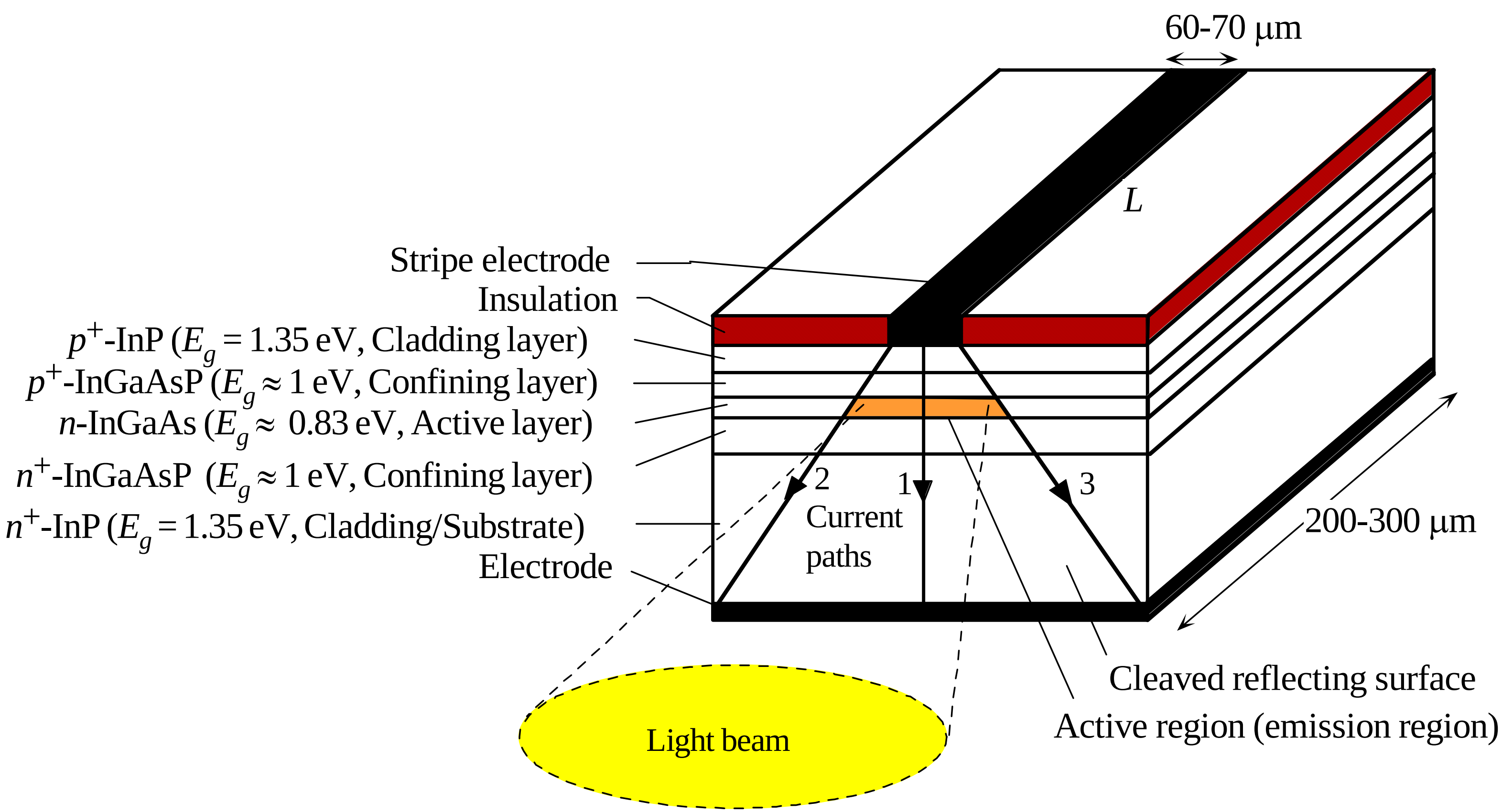
Typical τ_c is 2-5 ns for InGaAsP LEDs. The corresponding LED modulation bandwidth is 50-140 MHz.

The two basic layouts of LEDs



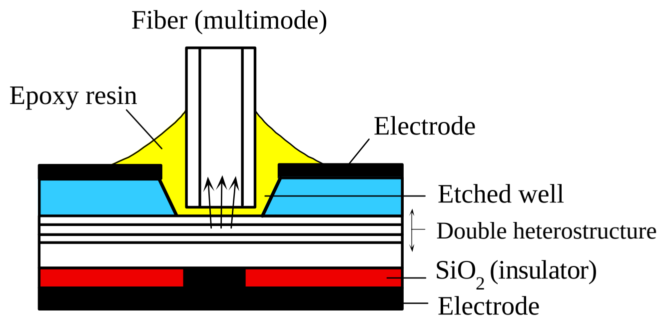
(a) Surface emitting LED (b) Edge emitting LED

1.5 micron ELED chip design



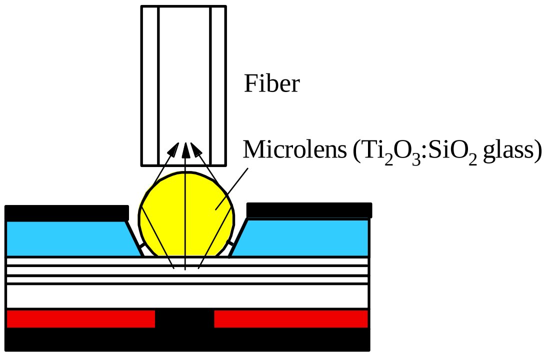
Schematic illustration of the the structure of a double heterojunction stripe contact edge emitting LED

Coupling light from LEDs



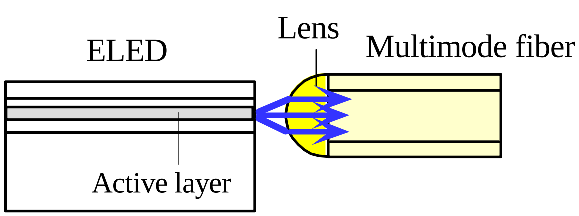
(a)

Light is coupled from a surface emitting LED into a multimode fiber using an index matching epoxy. The fiber is bonded to the LED structure.

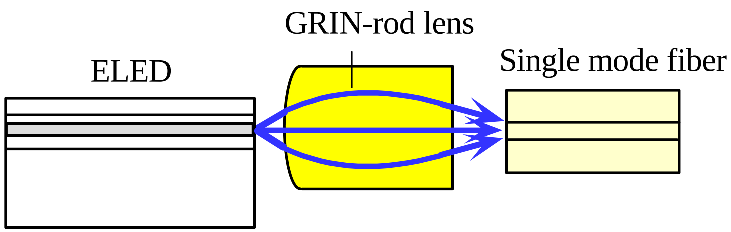


(b)

A microlens focuses diverging light from a surface emitting LED into a multimode optical fiber.



(a)



(b)

Light from an edge emitting LED is coupled into a fiber typically by using a lens or a GRIN rod lens.

Some fiber coupling estimates for LEDs

An LED acts as a Lambertian source due to its incoherent nature with an angular distribution $S(\theta) = S_0 \cos\theta$

The coupling efficiency for such as source is $\eta_c = (NA)^2$. The NA for optical fibers is typically 0.1-0.3, and thus the coupling efficiency is in the single digit percent range. (ouch!). The typical launch power into a fiber for an LED is 0.1 mW even though the emitted power from the device can be 10 mW.