Lecture 8

Light Emitting Diodes

ECE 325

OPTOELECTRONICS

Menoufia University

Kasap–3.11, 3.13, 3.14, 3.15, 3.16 and 3.17

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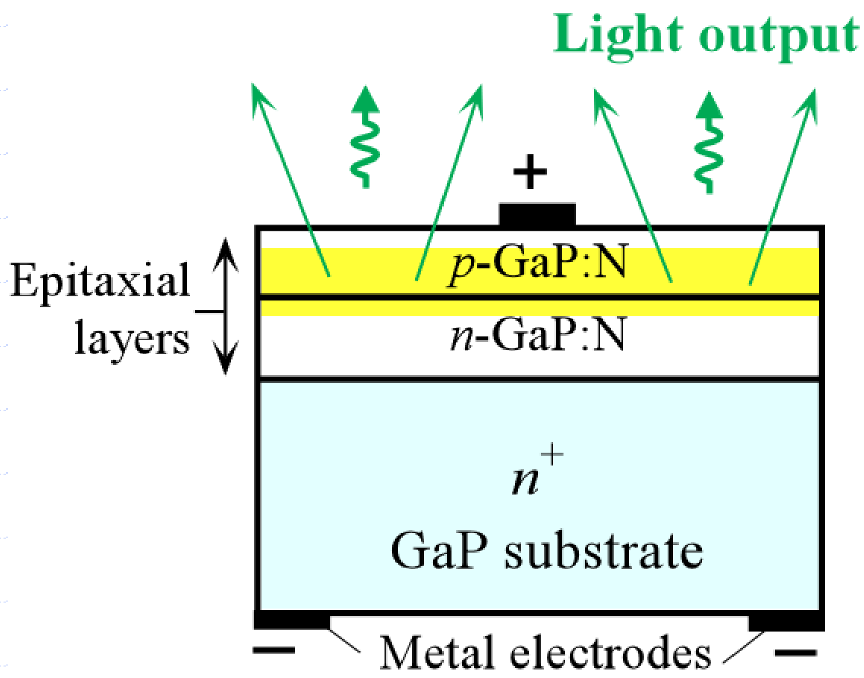
Light Emitting Diodes

- A **l**ight **e**mitting **d**iode (LED) is a *pn* junction diode typically made from a direct bandgap semiconductor in which the electron hole pair (EHP) recombination results in the emission of a photon.
- Emitted photon energy

$$h\nu \approx E_g$$

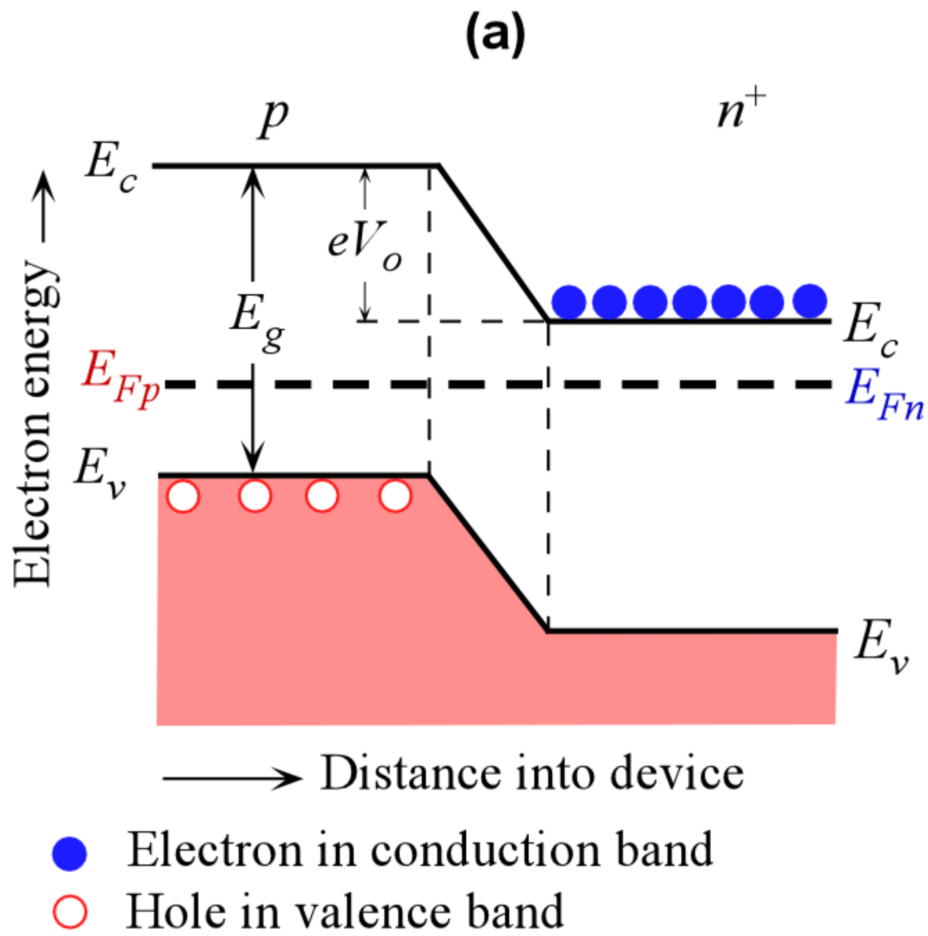
Bandgap energy



Band Diagram of a *pn*+ Junction Device

pn+ junction device:

- The *n*+ side is more heavily doped than the p-side.
- **The depletion region in a *pn*+ device extends mainly into the *p*-side.**



(a) Without any bias:

- Uniform Fermi level
- *PE* barrier = eV_0

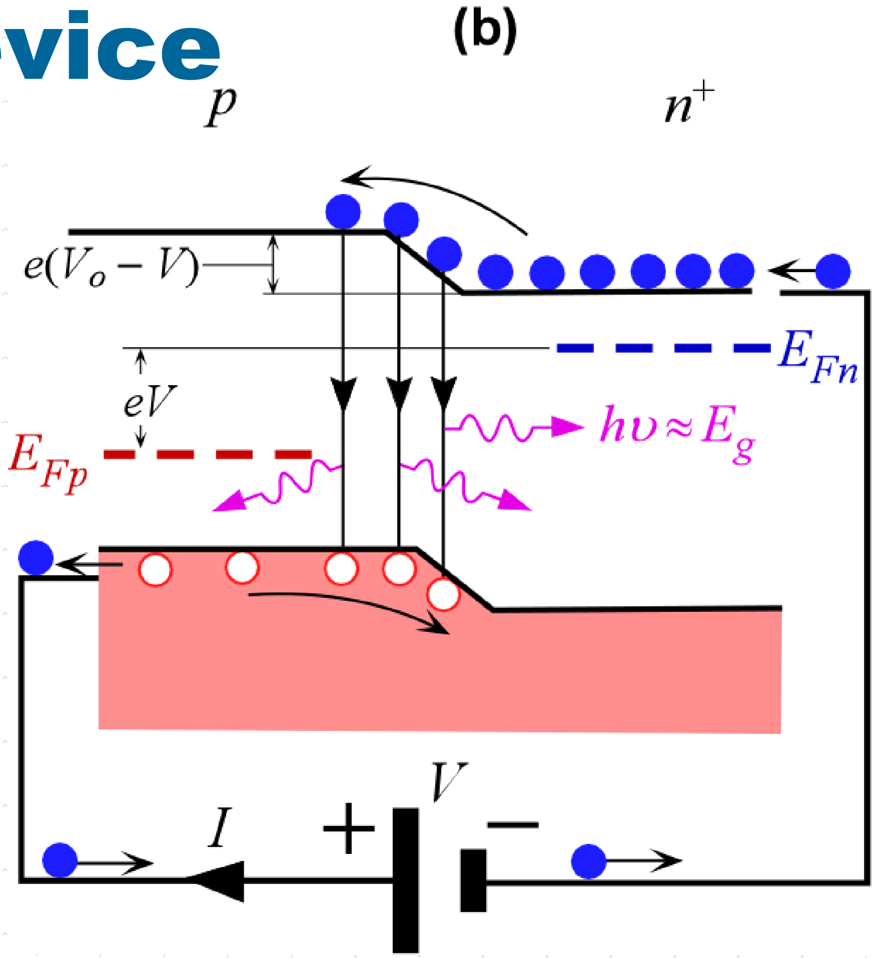
⇨ Built-in potential V_0 prevents electrons from diffusing from n^+ to p side.

Band Diagram of a pn^+ Junction Device

(b) Forward bias

- Built in potential $V_0 \rightarrow V_0 - V$

⇨ It allows the electrons from the n^+ side to diffuse or become injected into the *p*-side.



- The recombination of injected electrons in the depletion region as well as in the neutral *p*-side results in the spontaneous emission of photons.

Active Region

- Recombination primary occurs within:
- ➢ The depletion region
- ➢ A volume extending over the diffusion length L_e of the electrons in the p-side
- The recombination zone is called the **active region**.

Injection Electroluminescence

- The phenomenon of light emission from EHP recombination as a result of <u>minority carrier injection</u>.
- Spontaneous emission process

⇨ The emitted photons are in **random direction**.

Homo and heterojunctions

- **Homojunction:**

  A junction (such as a *pn* junction) between two differently doped semiconductors that are of the same material (same bandgap E_g)

- **Heterojunction:**

  A junction between two different bandgap semiconductors

- **Heterojunction device (HD):**

  A semiconductor device structure that has junctions between different bandgap materials

- The refractive index n of semiconductor material depends on its bandgap E_g:

$$n \downarrow \text{ as } E_g \uparrow$$

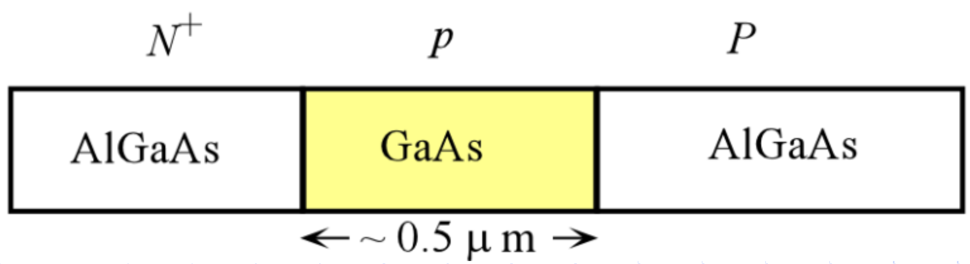
- By constructing LEDs from heterostructures, we can engineer a dielectric waveguide within the device and thereby channel photons out from the recombination region.

Drawbacks of homojunction LEDs

- The p-region must be narrow to allow the photons to escape without much reabsorption.
- When the p-side is narrow, some of the injected electrons in the p-side reach the surface by diffusion and recombine through crystal defects near the surface.
- Radiationless recombination process decreases the light output.
- If the recombination occurs over a relative large volume (or distance), due to long electron diffusion lengths, then the chances of reabsorption of emitted photons becomes higher.
- The amount of reabsorption increases with the material volume.

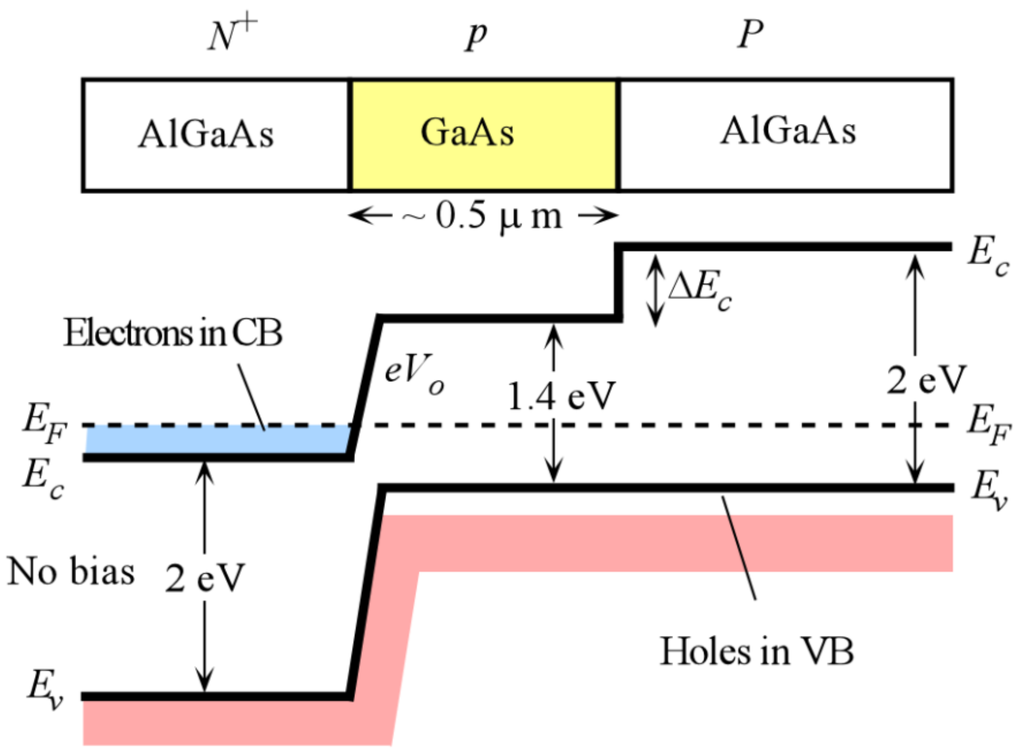
Double heterostructure (DH) device

- DH device based on two junctions between different semiconductor materials with different bandgaps.
- Different materials
  - *Eg* (AlGaAs) ≈ 2 eV
  - *Eg* (GaAs) ≈ 1.4 eV



- Two heterjunctions
  - n^+ p heterojunction between n^+-AlGaAS and *p*-GaAs
  - *p p* heterojunction between *p*-GaAS and *p*-AlGaAs
- *p*-GaAS thin layer
  - a fraction of µm
  - lightly doped

Band diagram with zero bias



(a) A double heterostructure diode has two heterojunctions which are between two different bandgap semiconductors (GaAs and AlGaAs)

(b) A simplified energy band diagram with exaggerated features. E_F must be uniform

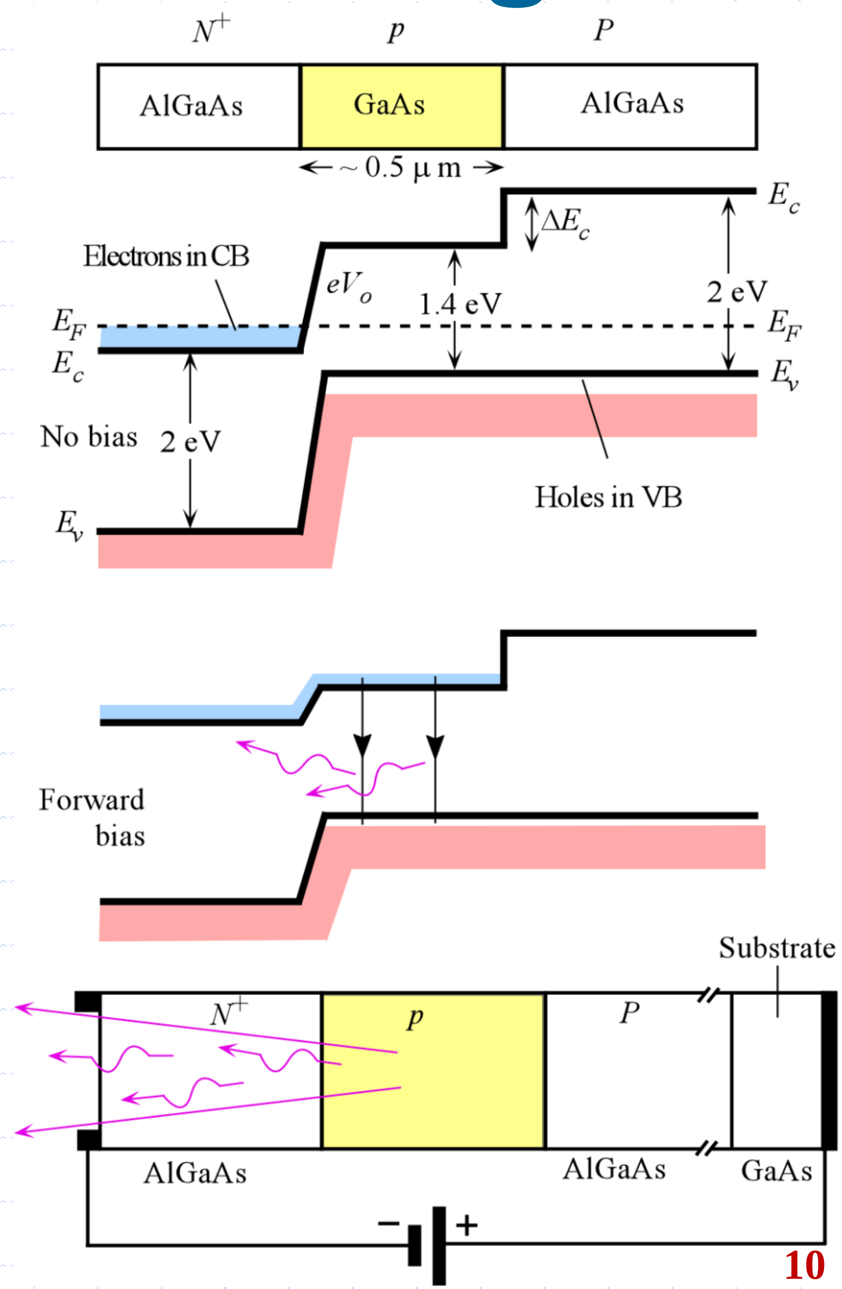
- No bias ⇨ Fermi level E_F = constant
- eV_0 : PE barrier between *n*$^+$-AlGaAS and *p*-GaAs
- ΔE_c = effective PE barrier between *p*-GaAS and *p*-AlGaAs

↑

Bandgap change between p-GaAs and p-AlGaAs

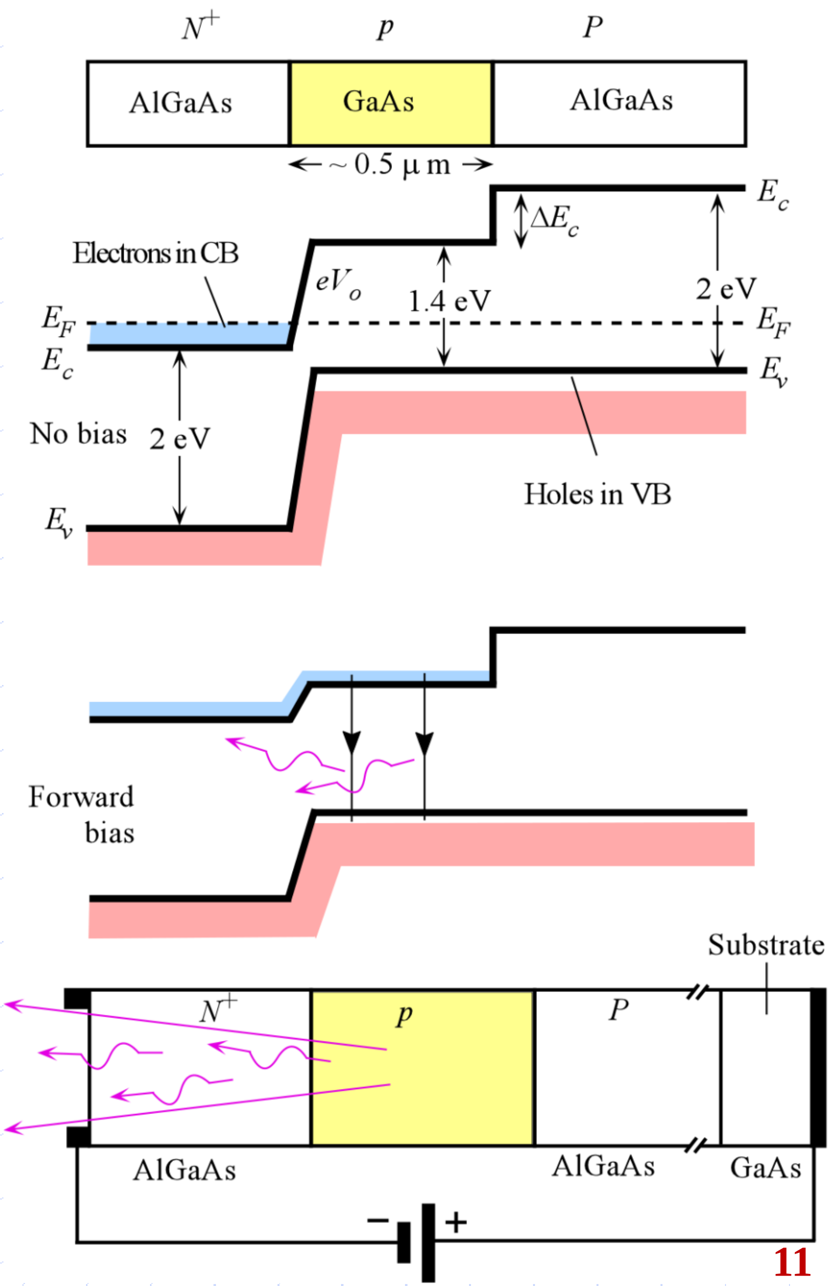
Forward biased band diagram

- PE barrier $eV_0 \rightarrow eV_0\text{-}V$
- Electrons in the CB of *n*+-AlGaAs are injected (by diffusion) into p-GaAs
- These electrons are confined to the CB of p-GaAs by the barrier ΔE_c
- Wide gap AlGaAs layers act as **confining layers**.



Double heterojunction LED

- EHP recombination presents in the p-GaAs layer
- E_g (AlGaAs) > E_g (GaAs)
- The emitted photons do not get reabsorbed as they escape the active region and can reach the surface of the device.
- Since light is also not absorbed in p-AlGaAs, it can be reflected to increase the light output.
- DH LED is much more efficient than homojunction LED



Photon energy, wavelength and color

Wavelength ranges and colors as usually specified for LEDs

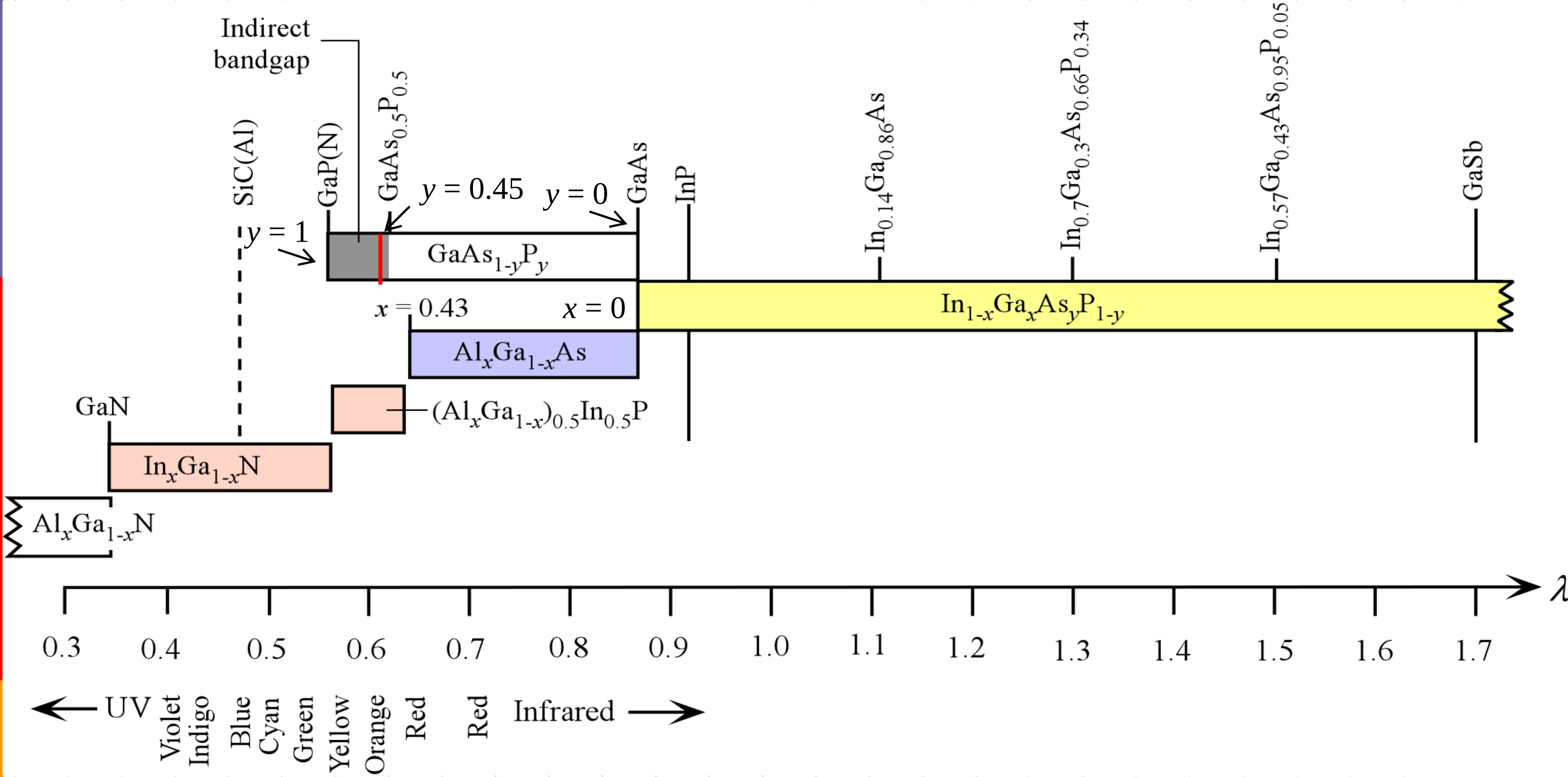
Color	Blue	Emerald Green	Green	Yellow	Amber	Orange	Red-Orange	Red	Deep red	Infrared
λ (nm)	$\lambda < 500$	530–564	565–579	580–587	588–594	595–606	607–615	616–632	632–700	$\lambda > 700$

$$E = h\nu = \frac{hc}{\lambda} = \frac{(4.14\times10^{-15}\ \text{eV}\cdot\text{s})\times(2.9979\times10^{17}\ \text{nm/s})}{\lambda}$$

$$= \frac{1240\ \text{eV}\cdot\text{nm}}{\lambda}$$

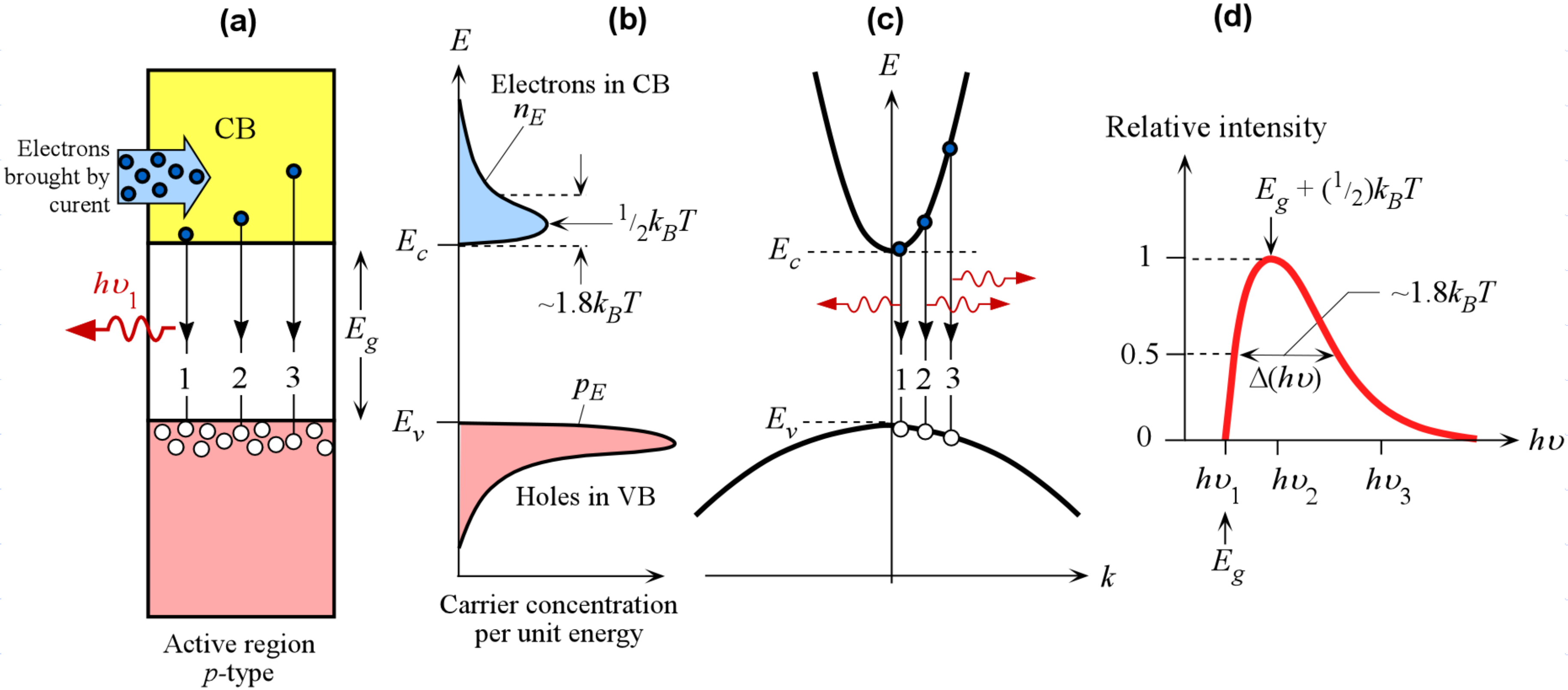
$$\Rightarrow \boxed{\lambda(\text{nm}) = \frac{1240\ \text{eV}\cdot\text{nm}}{E(\text{eV})}}$$

LED Materials



Free space wavelength coverage by different LED materials from the visible spectrum to the infrared including wavelengths used in optical communications. Hatched region and dashed lines are indirect E_g materials. Only material compositions of importance have been shown.

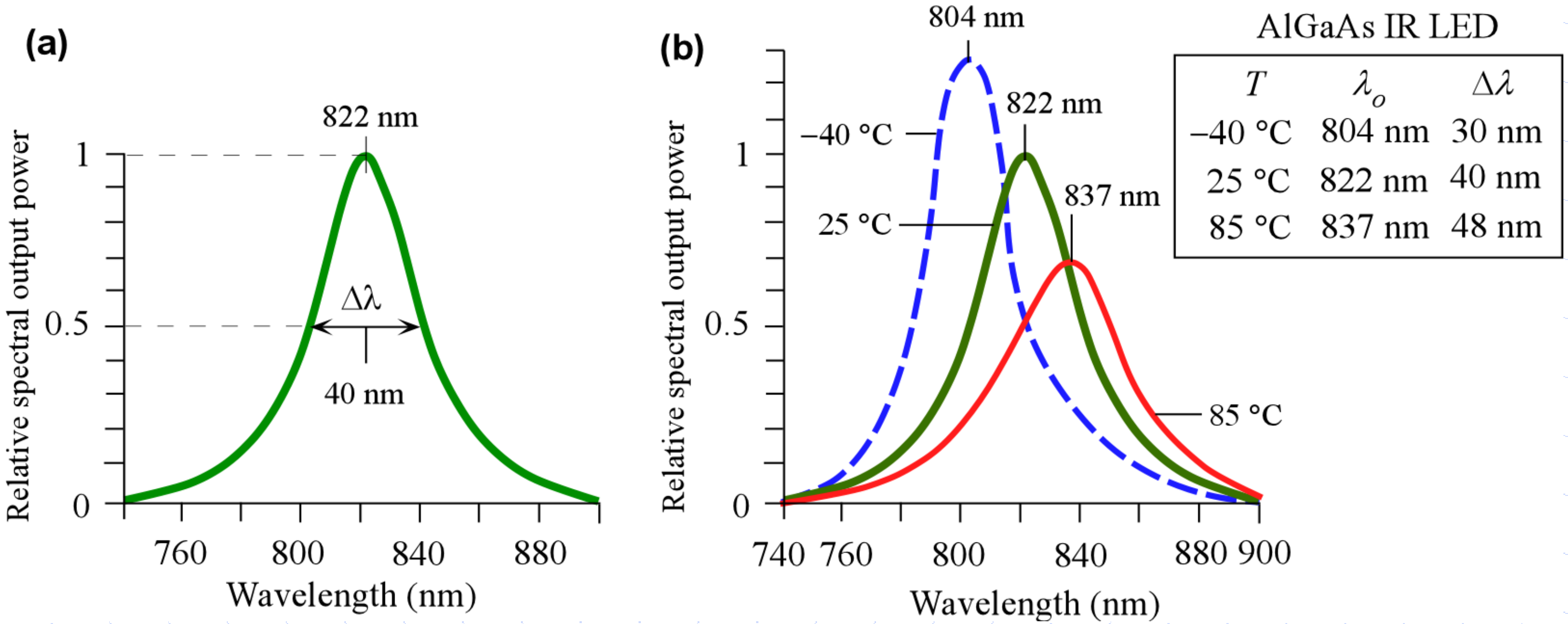
Emission Spectrum



$$h\upsilon_o \approx E_g + \frac{1}{2}k_BT$$

$$h\Delta\upsilon = mk_BT$$

Emission Spectrum



(a) A typical output spectrum (relative intensity vs. wavelength) from an IR (infrared) AlGaAs LED. (b) The output spectrum of the LED in (a) at 3 temperatures: 25 °C, –40 °C and 85 °C. Values normalized to peak emission at 25 °C. The spectral widths are FWHM.

$$E_g = E_{go} - \frac{AT^2}{B+T}$$

E_{go} is the bandgap at $T = 0$ K, and A and B are material-specific constants

EXAMPLE: Dependence on the emission peak and linewidth on temperature

Using the Varshni equation, Eq. (3.11.2), $E_g = E_{go} - AT^2/(B + T)$, find the shift in the peak wavelength (λ_o) emitted from a GaAs LED when it is cooled from 25 °C to -25 °C. The *Varshni constants* for GaAs are, E_{go} = 1.519 eV, $A = 5.41 \times 10^{-4}$ eV K^{-1}, B = 204 K.

Solution

At T = 298 K, using the Varshni equation

$$E_g = E_{go} - AT^2/(B + T)$$

$$= 1.519\text{ eV} - (5.41 \times 10^{-4}\text{ eV K}^{-1})(298\text{ K})^2/(204\text{ K} + 298\text{ K}) = 1.423\text{ eV}.$$

At 298 K, (1/2) k_BT = 0.0128 eV. The peak emission is at $h\upsilon_o \approx E_g$ + (1/2) k_BT. Using $\upsilon_o = c/\lambda_o$, we get

$$\lambda_o = \frac{ch}{(E_g + \frac{1}{2}k_BT)} = \frac{(3\times10^8\text{ m s}^{-1})(6.626\times10^{-34}\text{ J s})/1.602\times10^{-19}\text{ eV J}^{-1})}{(1.4223\text{eV} + 0.0128\text{eV})} = \mathbf{864.2\text{ nm}}$$

At −25 °C or , 248 K, ($^1/_2$) k_BT = 0.0107 eV, repeating the above calculation,

$$E_g = 1.519\text{ eV} - (5.41 \times 10^{-4}\text{ eV K}^{-1})(248\text{ K})^2/(204\text{ K} + 248\text{ K}) = \mathbf{1.445\text{ eV}}$$

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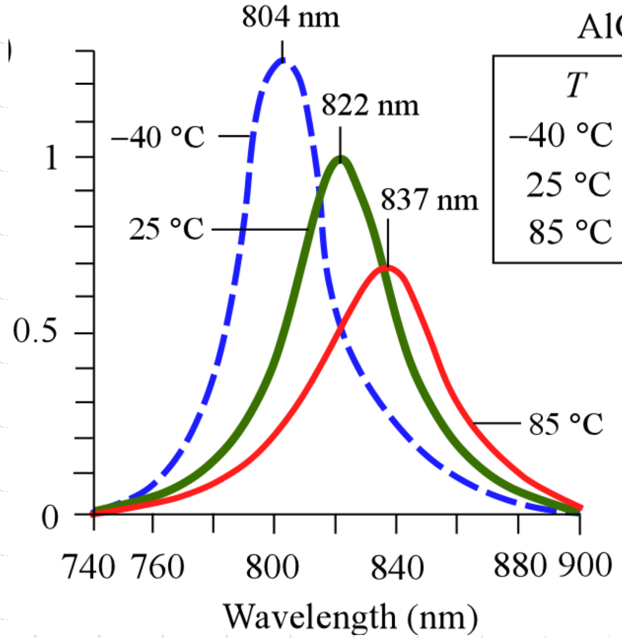
EXAMPLE: Dependence on the emission peak and linewidth on temperature

Solution (continued)

and the new peak emission wavelength λ_0' is

$$\lambda_o' = \frac{(3\times10^8\ \mathrm{m\,s^{-1}})(6.626\times10^{-34}\ \mathrm{J\,s})/(1.602\times10^{-19}\ \mathrm{eV\,J^{-1}})}{(1.445\mathrm{eV} + 0.01069\mathrm{eV})} = 852.4\ \mathrm{nm}$$

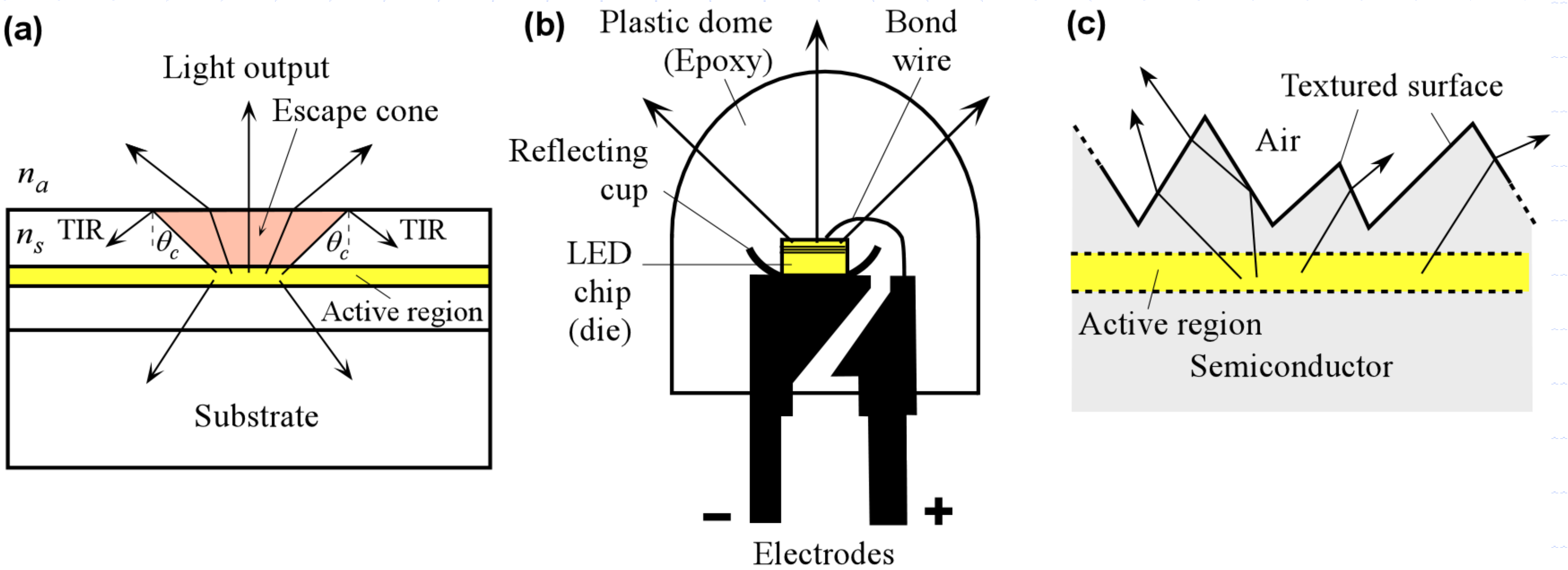
The change $\Delta\lambda = \lambda_o - \lambda_0'$ = 864.2 – 852.4 = **11.8 nm** over **50 °C**, or **0.24 nm / °C**.



T	λ_o	$\Delta\lambda$
–40 °C	804 nm	30 nm
25 °C	822 nm	40 nm
85 °C	837 nm	48 nm

The examination of the Figure 3.32(b) shows that the change in the peak wavelength per unit temperature in the range –40 °C to 85 °C is roughly the same. Because of the small change, we kept four significant figures in E_g and λ_o calculations.

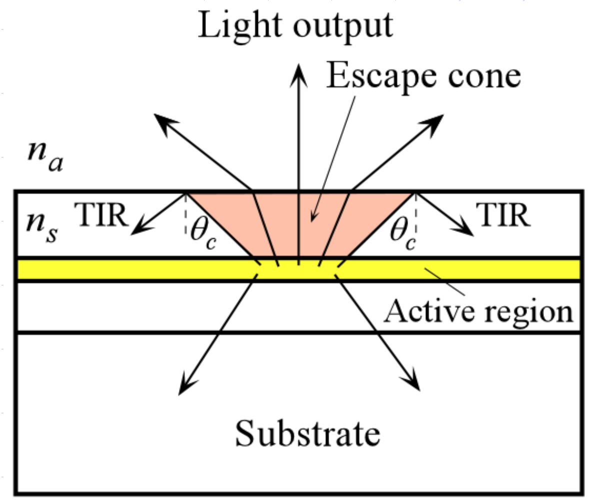
Light Extraction



(a) Some of the internally generated light suffers total internal reflection (TIR) at the semiconductor/air interface and cannot be emitted into the outside. (b) A simple structure that overcomes the TIR problem by placing the LED chip at the centre of a hemispherical plastic dome. The epoxy is refractive index matched to the semiconductor and the rays reaching the dome's surface do not suffer TIR. (b) An example of a textured surface that allows light to escape after a couple of (or more) reflections (highly exaggerated sketch).

EXAMPLE: Light extraction from a bare LED chip

As shown in (a), due to total internal reflection (TIR) at the semiconductor- air surface, only a fraction of the emitted light can escape from the chip. The critical angle θ_c is determined by $\sin\theta_c = n_a/n_s$ where n_a and n_s are the refractive indices of the ambient (*e.g.* for air, $n_a = 1$) and the semiconductor respectively. The light within the **escape cone** defined by θ_c can escape into the ambient without TIR as indicated in (a). To find the fraction of light within the escape cone we need to consider solid angles, which leads to $(1/2)[1-\cos\theta_c]$.



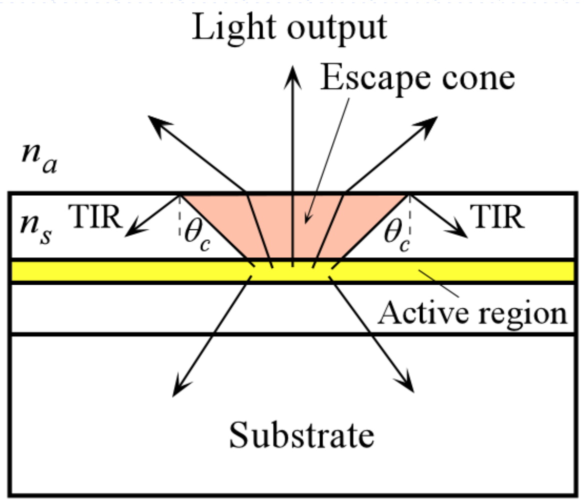
Further, suppose that T is the average light transmittance of the n_s- n_a interface for those rays within the escape cone, then for a simple bare chip,

$$\textbf{Light extraction ratio} \approx (1/2)[1-\cos\theta_c] \times T \qquad (1)$$

Estimate the extraction ratio for a GaAs chip with $n_s = 3.4$ and air as ambient ($n_a = 1$) and then with epoxy dome with $n_a = 1.8$.

EXAMPLE: Light extraction from a bare LED chip

Solution



First note that $\theta_c = \arcsin(n_a/n_s) = \arcsin(1/3.4) = 17.1°$. For T we will assume near- normal incidence (somewhat justified since the angle 17.1° is not too large) so that from Chapter 1,

$$T = 4n_s n_a/(n_s + n_a)^2 = 4(3.4)(1)/(3.4 + 1)^2 = 0.702$$

Using Eq.(1),

Light extraction ratio

$$\approx (1/2)[1-\cos\theta_c] \times T = (1/2)[1-\cos(17.1°)] \times 0.702$$

$\approx$ **0.0155** or **1.6%**

It is clear that only 1.6% of the generated light power is extracted from a bare chip, which is disappointingly small. The technological drive is therefore to improve light extraction as much as possible. If we now repeat the calculation for $n_a = 1.8$, *we would find,* $q_c = 32°$, *and 6.9% light extraction.*

LED PARAMETERS

Internal quantum efficiency (IQE) η_{IQE}

$$\eta_{\text{IQE}} = \frac{\text{Rate of radiative recombination}}{\text{Total rate of recombination (radiative and nonradiative)}}$$

$$\eta_{\text{IQE}} = \frac{\tau_r^{-1}}{\tau_r^{-1} + \tau_{nr}^{-1}}$$

$$\eta_{\text{IQE}} = \frac{\text{Photons emitted per second}}{\text{Total carriers lost per second}} = \frac{\Phi_{\text{ph}}}{I/e} = \frac{P_{o(\text{int})}/h\upsilon}{I/e}$$

External Quantum Efficiency

External quantum efficiency (EQE) η_{EQE} of an LED represents the efficiency of conversion from electrical quanta, *i.e.* electrons, that flow in the LED to optical quanta, *i.e.* photons, that are emitted into the outside world.

Actual optical power emitted to the ambient = Radiant flux = P_o (Φ_e is also used)

$P_o/h\upsilon$ is the number of emitted photons per second

I/e is the number of electrons flowing into the LED

$$\eta_{\mathrm{EQE}} = \frac{P_o / h\upsilon}{I / e}$$

EXTRACTION EFFICIENCY

Extraction ratio, or the **extraction efficiency** (EE), η_{EE}

$$\eta_{\mathrm{EE}} = \frac{\text{Photons emitted externally from the device}}{\text{Photons generated internally by recombination}}$$

$$P_o = \eta_{\mathrm{EE}} P_{o(\mathrm{int})} = h\upsilon\eta_{\mathrm{EE}}\eta_{\mathrm{IQE}}(I/e)$$

POWER CONVERSION EFFICIENCY

Power conversion efficiency (PCE)

Power efficiency

η_{PCE}

Efficiency of conversion from the input of electrical power to the output of optical power

$$\eta_{\text{PCE}} = \frac{\text{Optical output power}}{\text{Electrical input power}} = \frac{P_o}{IV} \approx \eta_{\text{EQE}}\left(\frac{E_g}{eV}\right)$$

LED BRIGHTNESS

Luminous flux Φ_{υ} is a measure of *visual* **brightness**, in lumens (lm), and is defined by

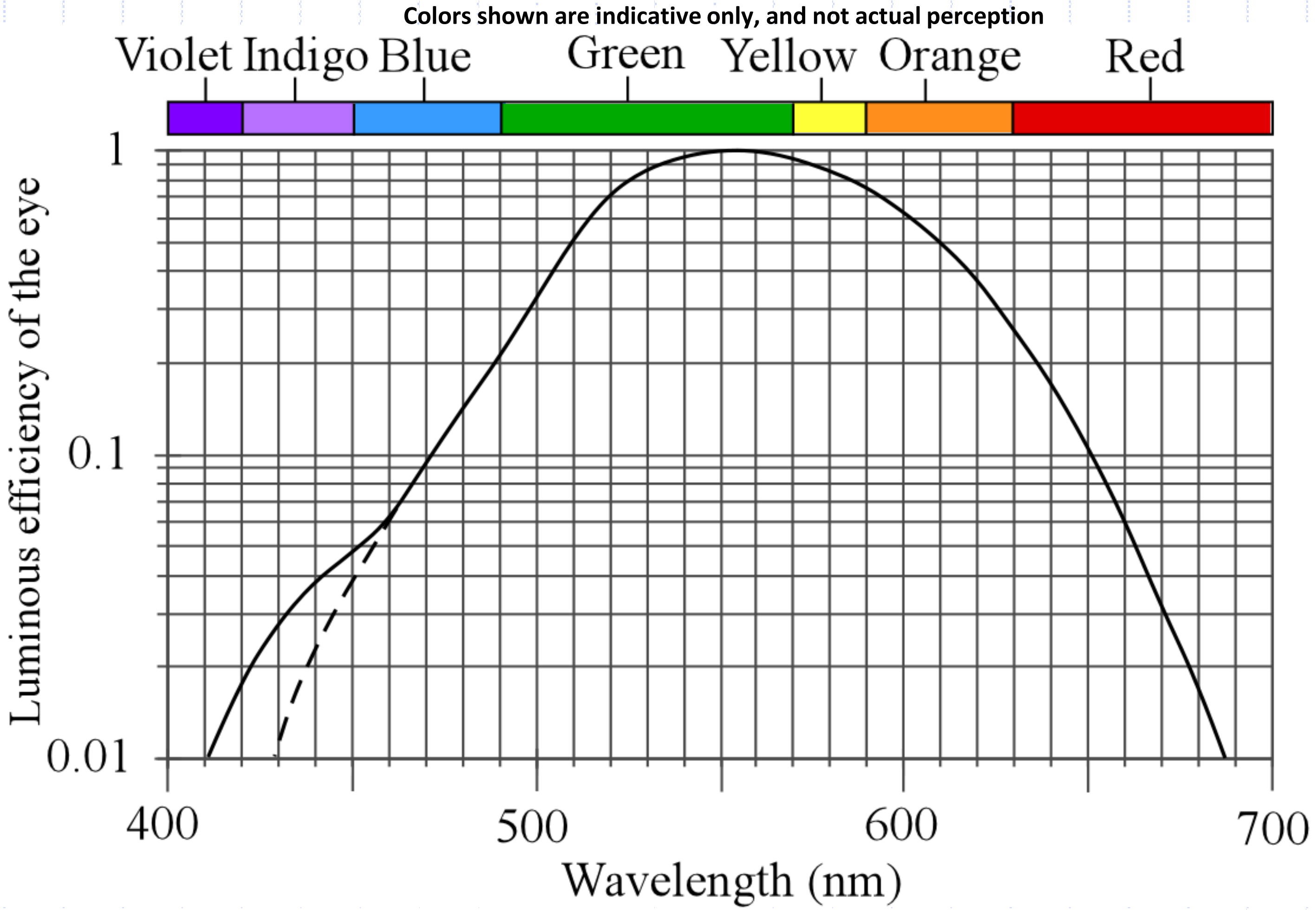
$$\Phi_{\upsilon} = P_o \times (683 \text{ lm W}^{-1}) \times V(\lambda)$$

$V(\lambda)$ = **relative luminous efficiency** or the relative sensitivity of an average light-adapted (photopic) eye, which depends on the wavelength

$V(\lambda)$ = **luminosity function** and the **visibility function**

$V(\lambda)$ is a Gaussian-like function with a peak of unity at 555

The luminous efficiency of the eye



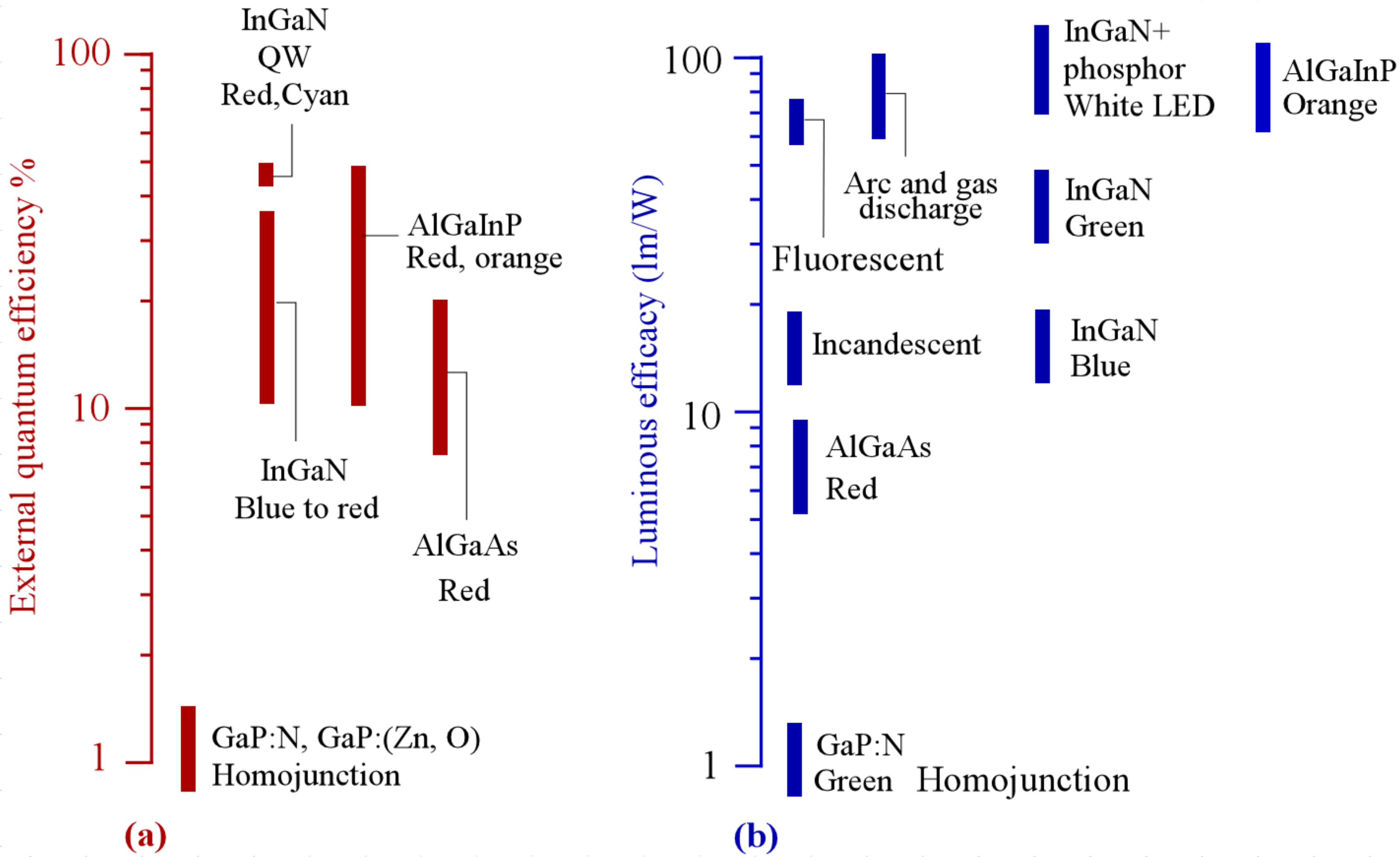
The luminous efficiency $V(\lambda)$ of the light-adapted (photopic) eye as a function of wavelength. The solid curve is the Judd-Vos modification of the CIE 1924 photopic photosensitivity curve of the eye. The dashed line shows the modified region of the original CIE 1924 curve to account for its deficiency in the blue-violet region. (The vertical axis is logarithmic)

LED BRIGHTNESS AND EFFICACY

Luminous efficacy

$$\eta_{\mathrm{LE}} = \frac{\Phi_v}{IV}$$

Luminous Efficacy



Typical (a) external quantum efficiency and (b) luminous efficacy of various selected LEDs, and how they stand against other light sources such as the fluorescent tube, arc and gas discharge lamps and the incandescent lamp.

EXAMPLE: LED brightness LED brightness

Consider two LEDs, one red, with an optical output power (radiant flux) of 10 mW, emitting at 650 nm, and the other, a weaker 5 mW green LED, emitting at 532 nm. Find the luminous flux emitted by each LED.

Solution

For the **red LED**, at λ = 650 nm, Figure 3.41 gives $V \approx 0.10$ so that from Eq. (3.14.8)

$$\Phi_\upsilon = P_o \times (633 \text{ lm W}^{-1}) \times V$$
$$= (10\times10^{-3} \text{ W})(683 \text{ lm W}^{-1})(0.10) = \mathbf{0.68 \text{ lm}}$$

For the **green LED**, λ = 532 nm, Figure 3.41 gives V $\approx$ 0.87 so that from Eq. (3.14.8)

$$\Phi_\upsilon = P_o \times (633 \text{ lm W}^{-1}) \times V$$
$$= (5\times10^{-3} \text{ W})(683 \text{ lm W}^{-1})(0.87) = \mathbf{3.0 \text{ lm}}$$

Clearly the **green LED** at half the power is 4 times brighter than the **red LED**.

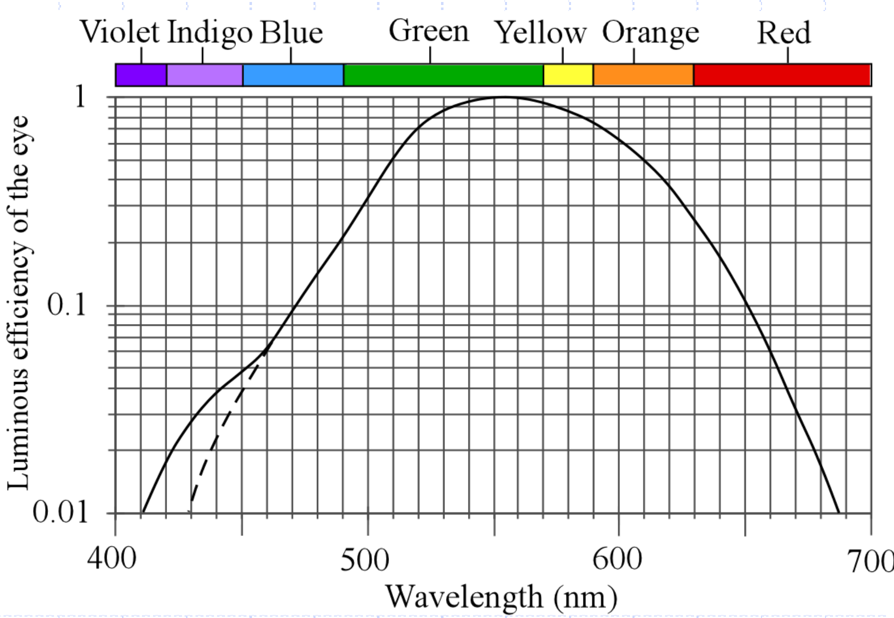
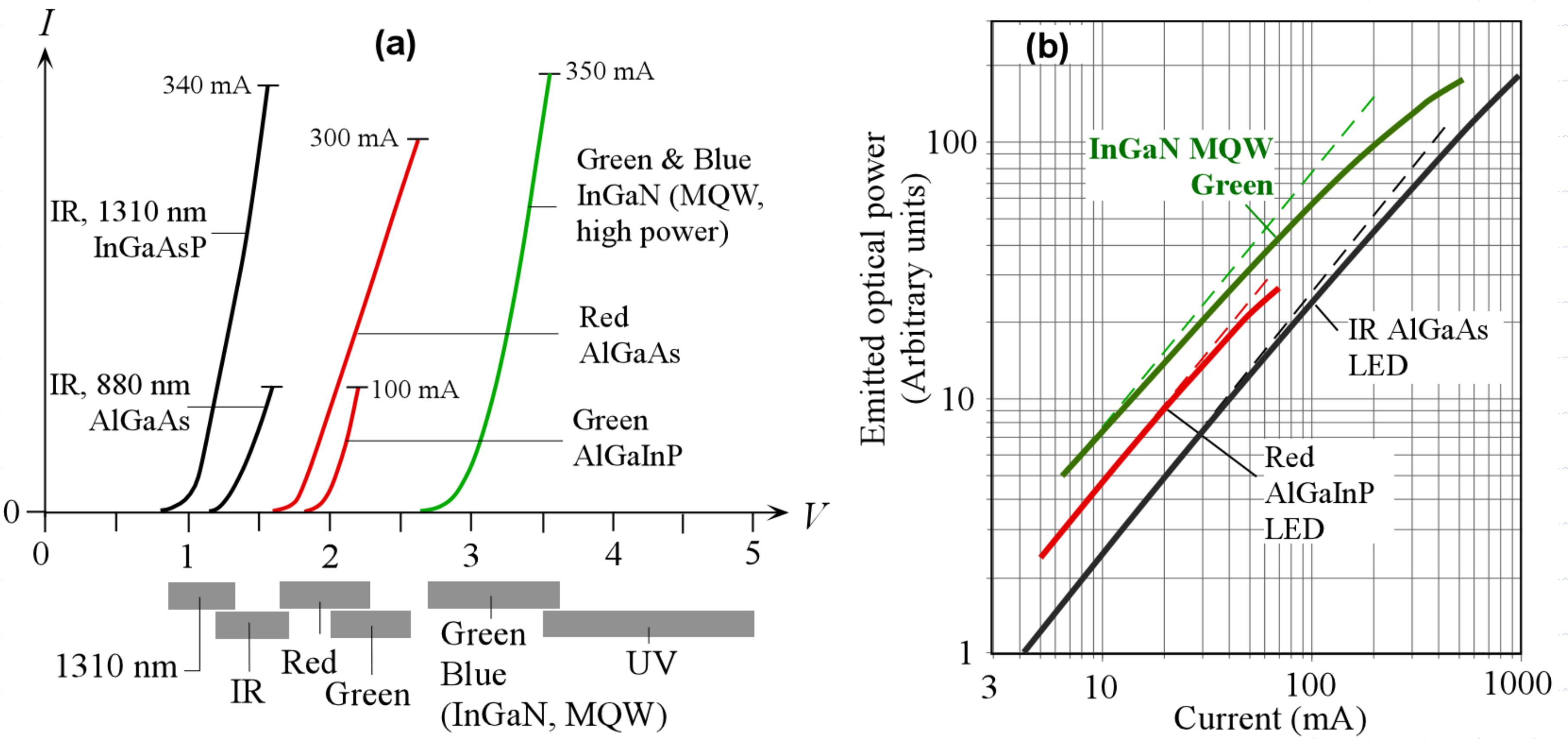


Figure 3.41

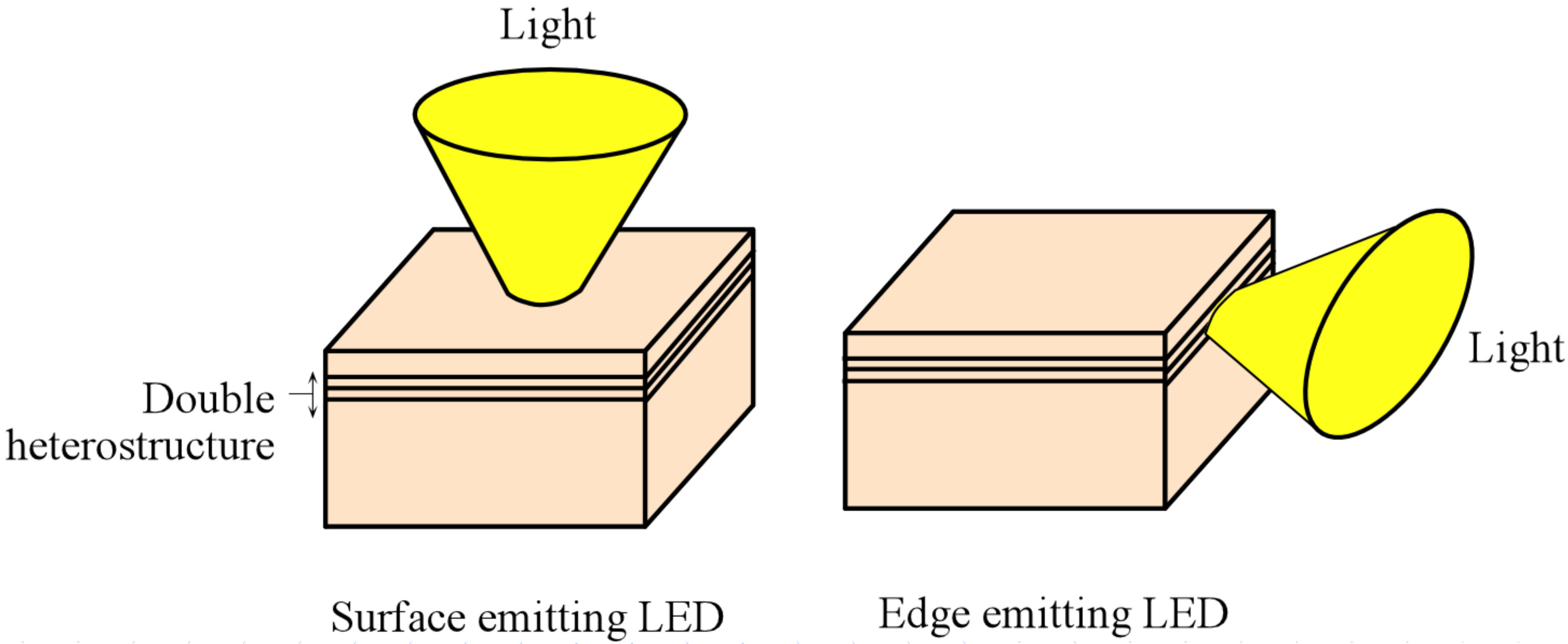
LED Characteristics: I vs. V



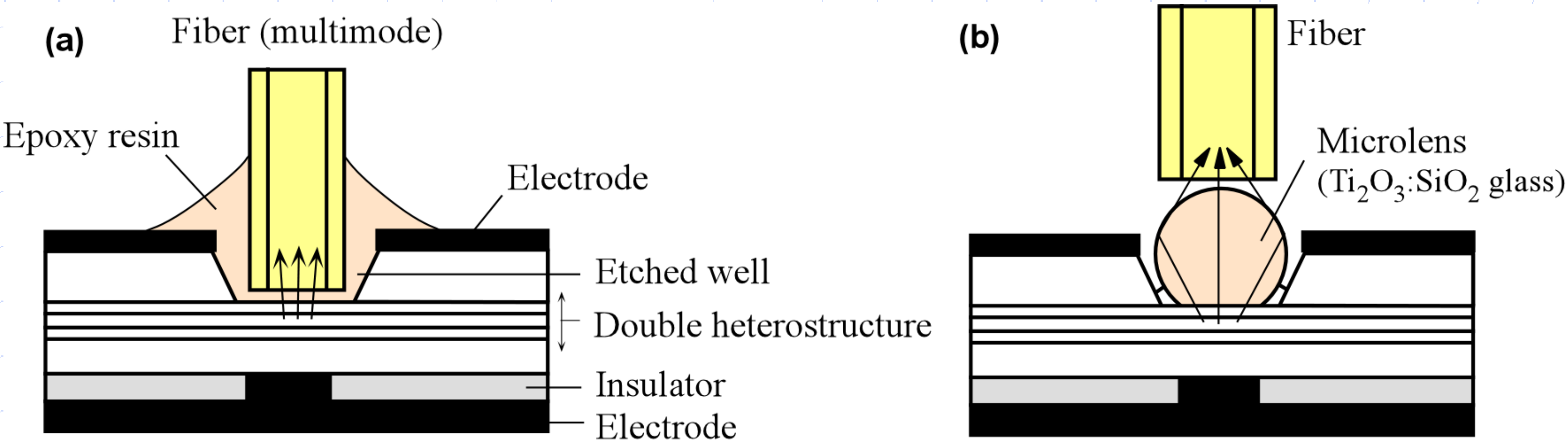
(a) Current-Voltage characteristics of a few LEDS emitting at different wavelengths from the IR to blue. (b) Log-log plot of the emitted optical output power vs. the dc current for three commercial devices emitting at IR (890 nm), Red and Green. The vertical scale is in arbitrary unit and the curves have been shifted to show the dependence of P_o on I. The ideal linear behavior $P_o \propto I$ is also shown.

LEDs for Optical Fiber Communication

- Two types of LEDs fabricated today
- Surface emitting LED (SLED)
- Edge emitting LED (ELED)

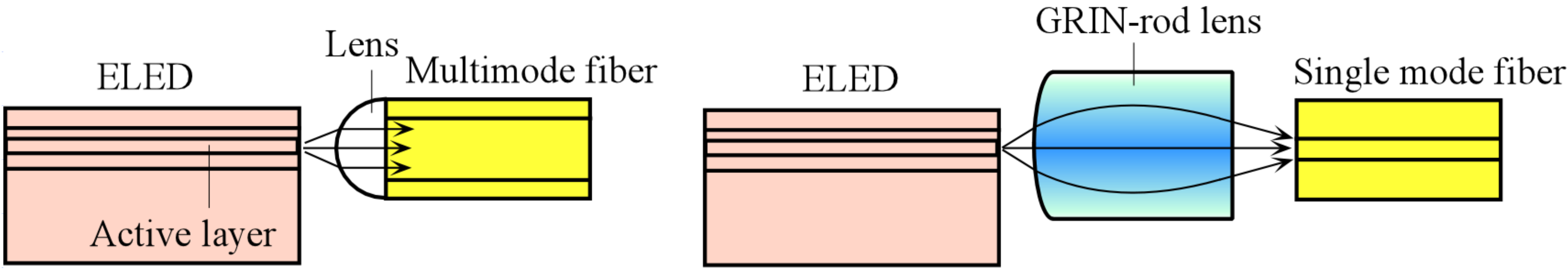


Surface Emitting LED (SLED)



Coupling of light from LEDs into optical fibers. (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.

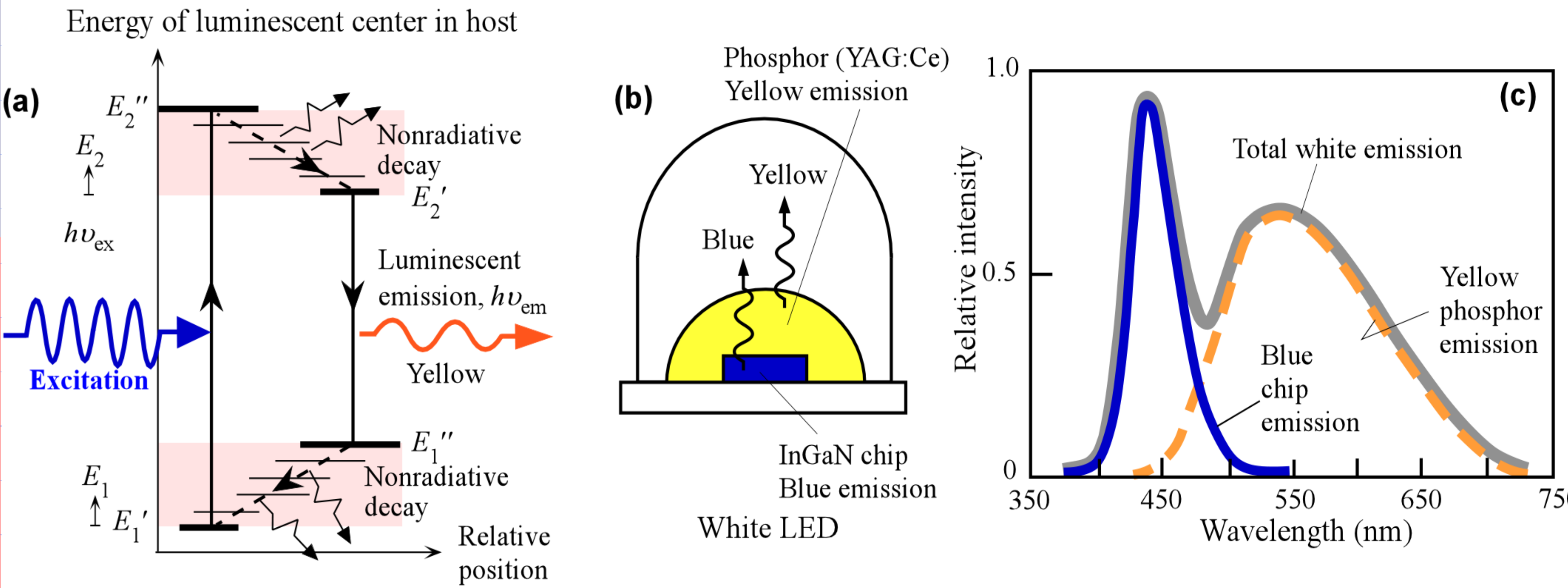
ELED Coupling into Fibers



(a) (b)

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

White LEDS



(a) A simplified energy diagram to explain the principle of photoluminescence. The activator is pumped from E_1' to E_2''. It decays nonradiatively down to E_2'. The transition from E_2' down to E_1'. (b) Schematic structure of a blue chip yellow phosphor white LED (c) The spectral distribution of light emitted by a white LED. Blue luminescence is emitted by GaInN chip and "yellow" phosphorescence is produced by phosphor. The combined spectrum looks "white". (Note: Orange used for yellow as yellow does not show well.)

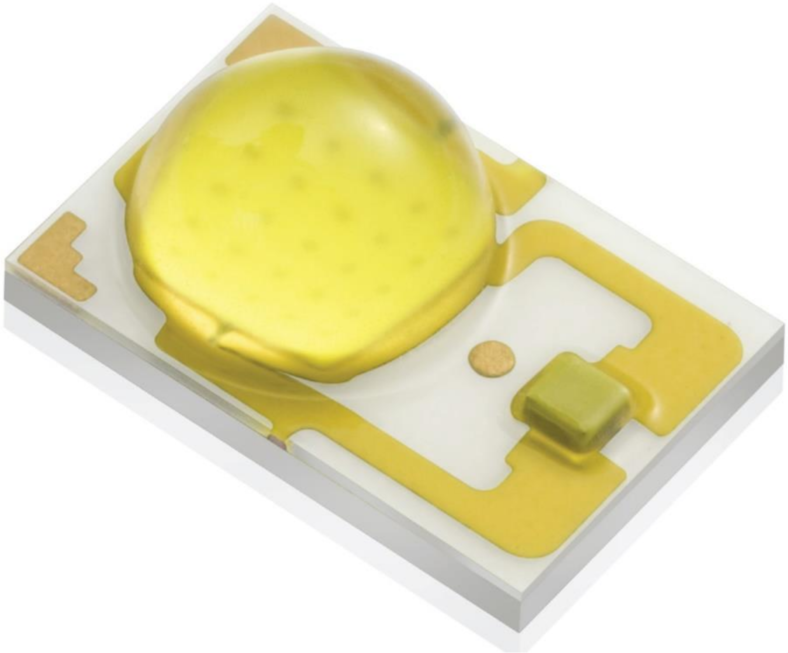
White LEDS

Photoluminescence is the emission of light by a material, called a **phosphor**, that has been first excited by light of higher frequency. Higher energy photons are first absorbed, and then lower energy photons are emitted.

Typically the emission of light occurs from certain dopants, impurities or even defects, called luminescent or **luminescence centers**, purposefully introduced into a **host matrix**, which may be a crystal or glass.

The luminescent center is also called an **activator**. Many phosphors are based on activators doped into a host matrix.

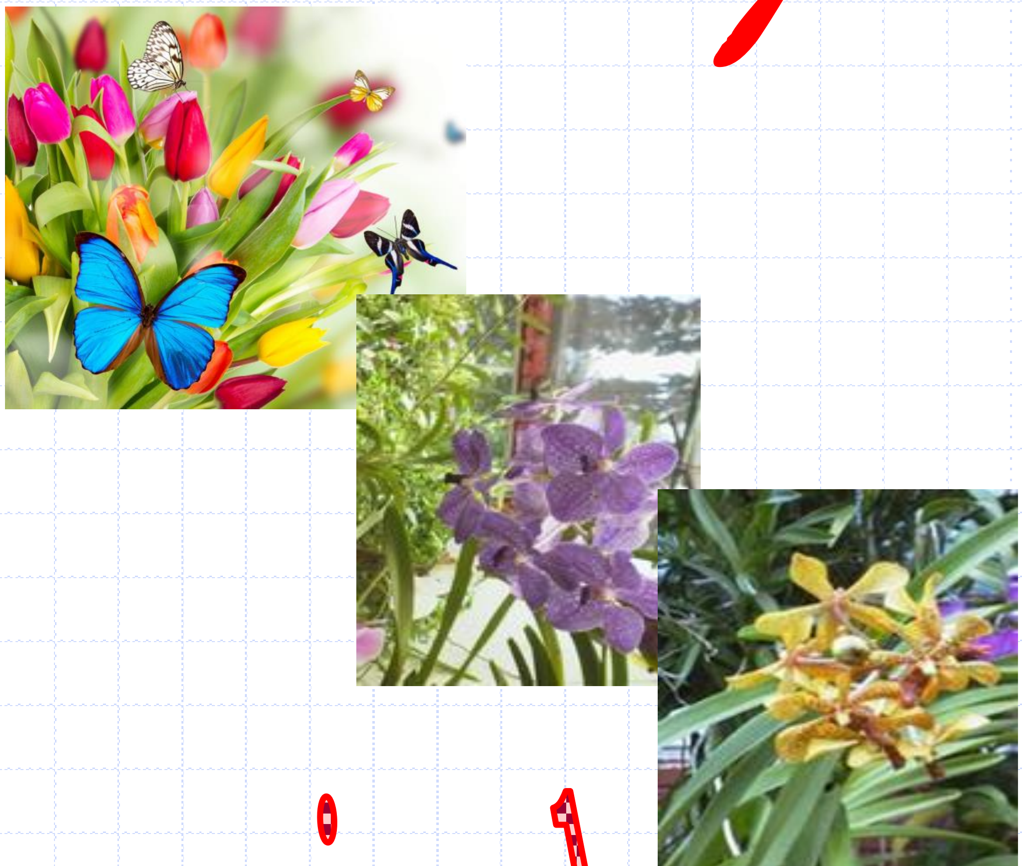
White LEDS

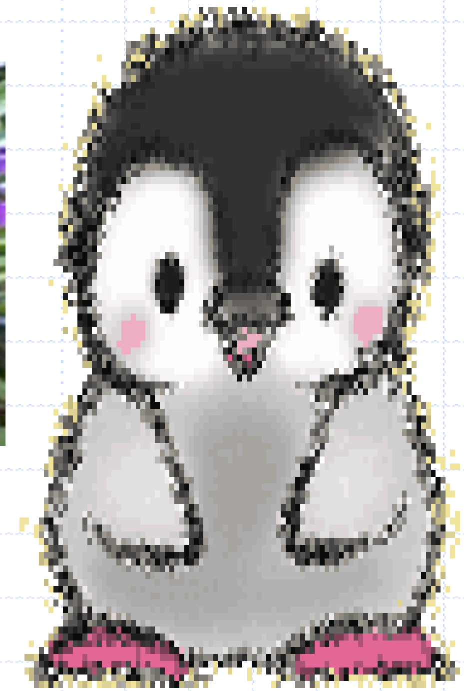


LUXEON Rebel ES white emitting LED (Courtesy of Philips Lumileds)

(Photo by SK)

Thank you





Have a nice day!