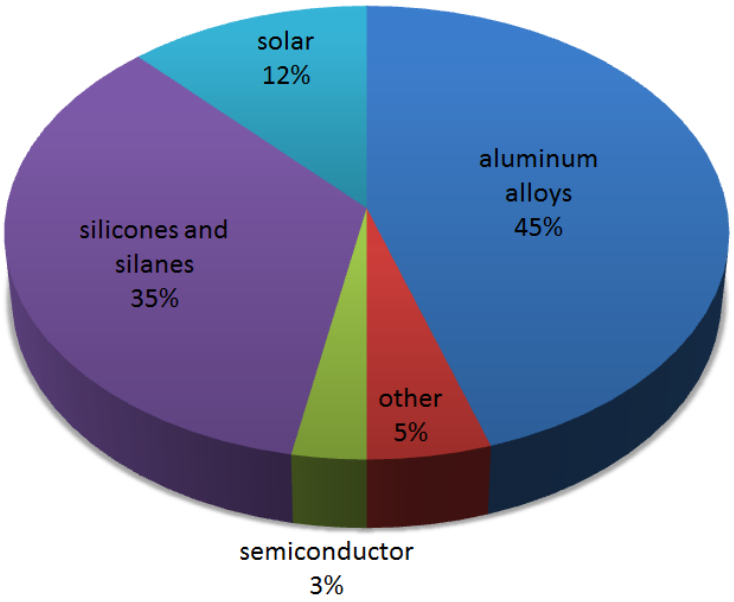
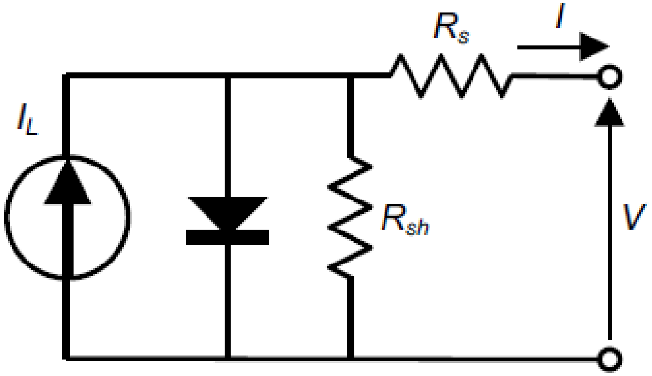
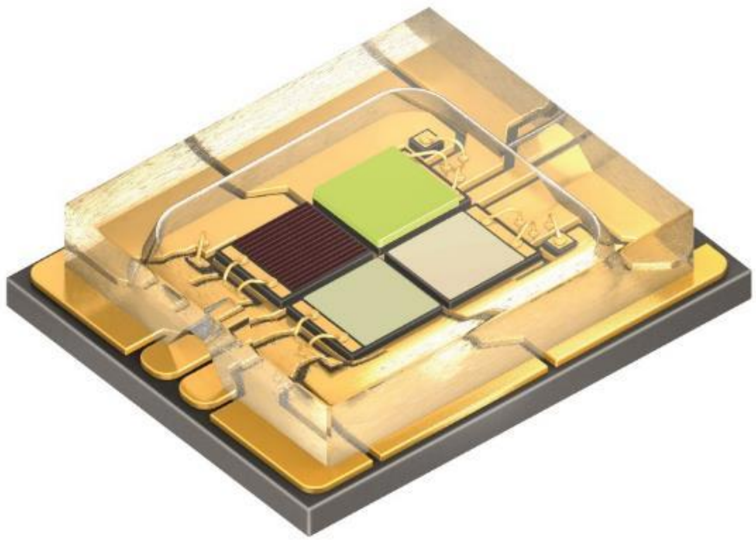
LEDs


solar
12%
aluminum
alloys
45%
silicones and
silanes
35%
other
5%
semiconductor
3%


R_s
I
I_L
R_{sh}
V

Light Emitting Diodes

This UV LED can emit 0.5 mW of radiation at 300 nm. The metal case is roughly 8.33 mm in diameter
Courtesy of Thorlabs

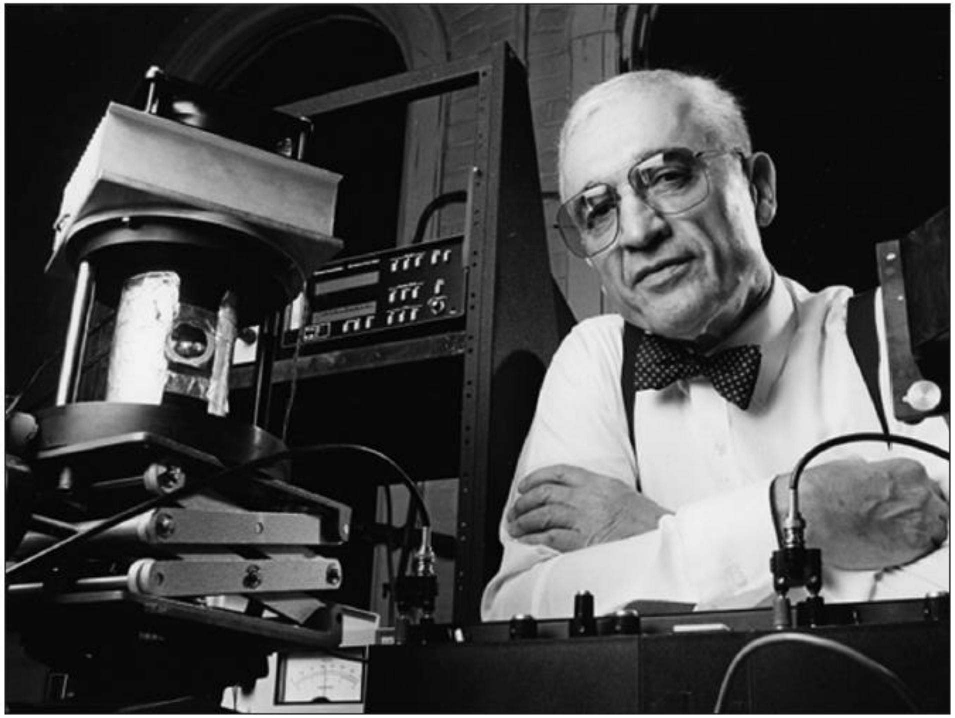


This multichip LED from Osram is used in various lighting applications, including microprojectors and stage lighting. The chip has three GaN and one AlGaInP LED devices, and can emit red, green, blue and white light. (The chip dimensions are approximately 5.8 × 4.7 × 1.3 mm.)

Courtesy of Osram

Fig 6.24

Light Emitting Diodes



Nick Holonyak Jr carried out the early work in the development of practical light emitting diodes (LEDs) in the visible spectrum during the 1960s while working as a consulting research scientist for General Electric Co. in Syracuse. He made his first visible laser-LED in 1962, which emitted red light. In the February 1963 issue of Readers Digest, Nick Holonyak Jr suggested that the incandescent light bulb will eventually be replaced by the LED. Since 1963, he has been at the University of Illinois at Urbana- Champaign where he currently holds the John Bardeen Endowed Chair. This photo was taken circa 1970–1975.

Courtesy of University of Illinois at Urbana- Champaign.

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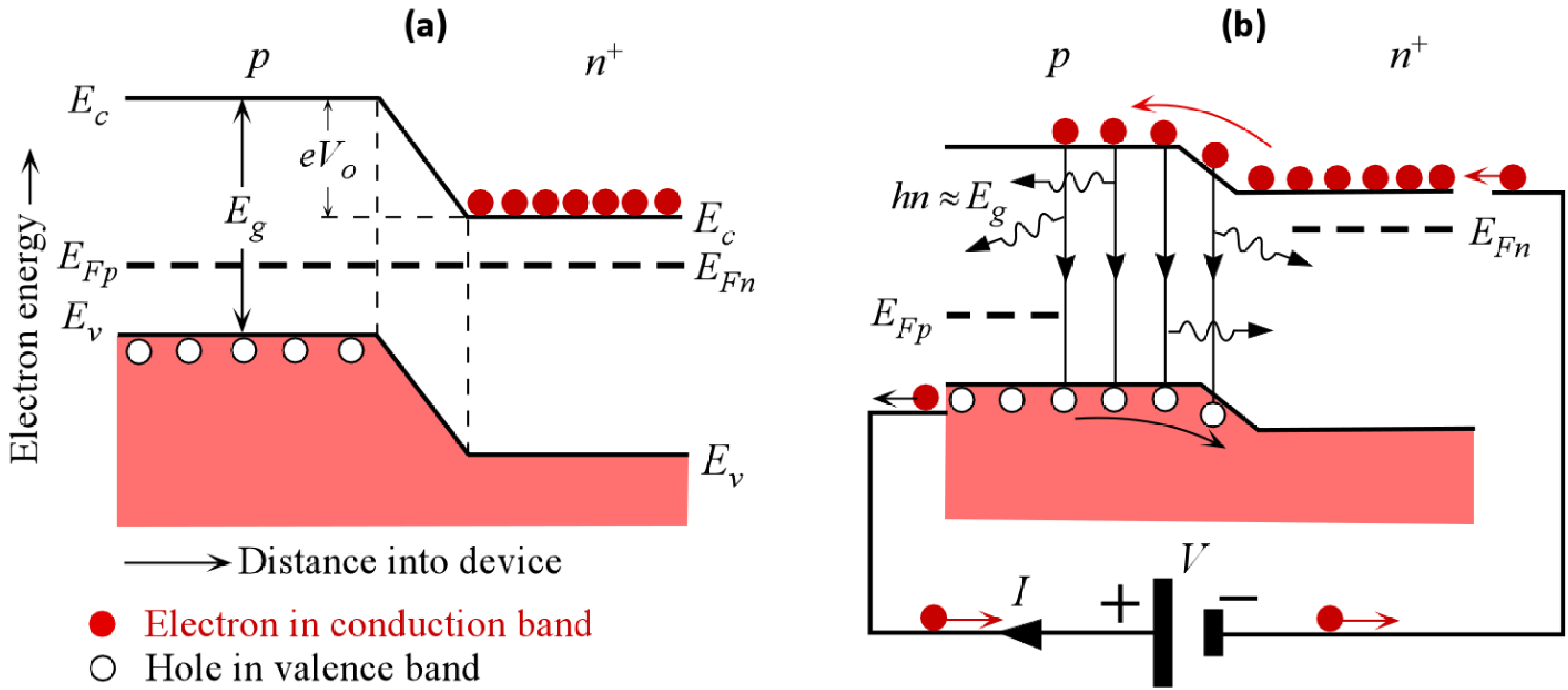
Fig 6.24

Direct Electron & Hole Recombination

injection electroluminescence



Energy band diagram of a *pn* (heavily *n*-type doped) junction. (a) No bias voltage. The p-layer is usually thin. The Fermi level is uniform across the whole device; $E_{Fn} = E_{Fp}$. (b) With forward bias *V*. Direct recombination around the junction and within the diffusion length of the electrons in the *p*-side leads to photon emission. The Fermi levels are separated and $E_{Fn} - E_{Fp} = eV$.

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Fig 6.24

Heterostructure Devices

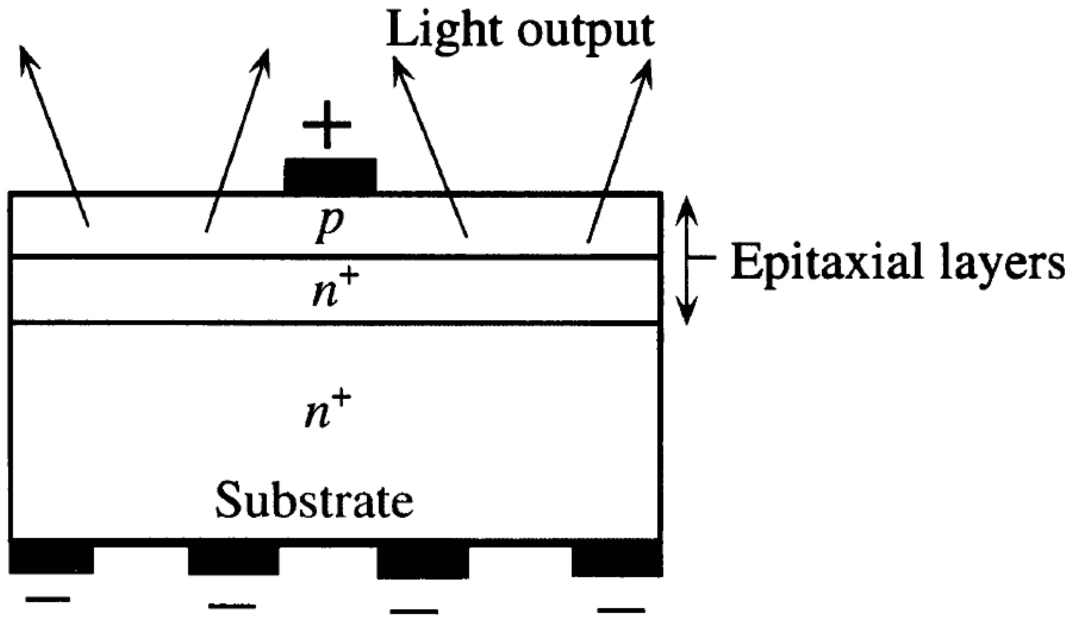

Figure 6.44 A schematic illustration of one possible LED device structure. First an n^+ layer is epitaxially grown on a substrate. A thin p layer is then epitaxially grown on the first layer.

- Due to random nature of the recombination process between electrons and holes, the emitted photons are in random directions; they result from spontaneous emission processes. The LED structure has to be such that the emitted photons can escape the device without being reabsorbed by the semiconductor material. We have to use **heterostructure** devices.

- The growth is done **epitaxially**; that is, the crystal of the new layer is grown to follow the structure of the substrate crystal.

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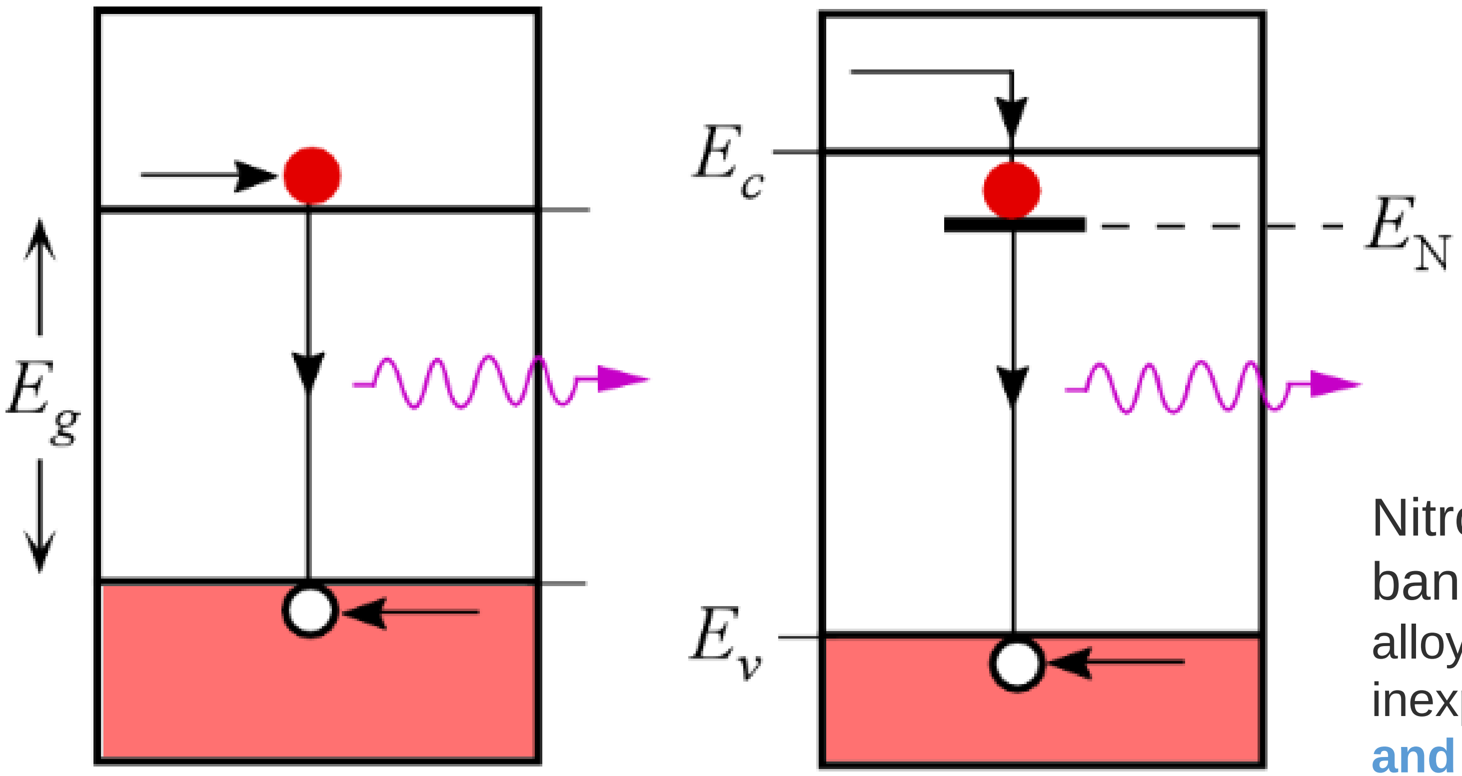
Light Emission in LEDs



$GaAs_{1-y}P_y$ ($y < 0.5$)

(a)

Direct bandgap

N doped GaP

(b)

Isoelectronic impurities

Nitrogen doped indirect bandgap GaAs P alloys are widely used in inexpensive **green, yellow, and orange** LEDs.

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Fig 6.27

Light Emission in LEDs

Table 6.2 Selected LED semiconductor materials

Semiconductor Active Layer	Structure	D or I	λ (nm)	$\eta_{external}$ (%)	Comments
GaAs	DH	D	870–900	10	Infrared (IR)
$Al_xGa_{1-x}As$ $(0 < x < 0.4)$	DH	D	640–870	3–20	Red to IR
$In_{1-x}Ga_xAs_yP_{1-y}$ $(y \approx 2.20x, 0 < x < 0.47)$	DH	D	1–1.6 μm	>10	LEDs in communications
$In_{0.49}Al_xGa_{0.51-x}P$	DH	D	590–630	>10	Amber, green, red; high luminous intensity
InGaN/GaN quantum well	QW	D	450–530	5–20	Blue to green
$GaAs_{1-y}P_y$ $(y < 0.45)$	HJ	D	630–870	< 1	Red to IR
$GaAs_{1-y}P_y$ $(y > 0.45)$ (N or Zn, O doping)	HJ	I	560–700	< 1	Red, orange, yellow
SiC	HJ	I	460–470	0.02	Blue, low efficiency
GaP (Zn)	HJ	I	700	2–3	Red
GaP (N)	HJ	I	565	< 1	Green

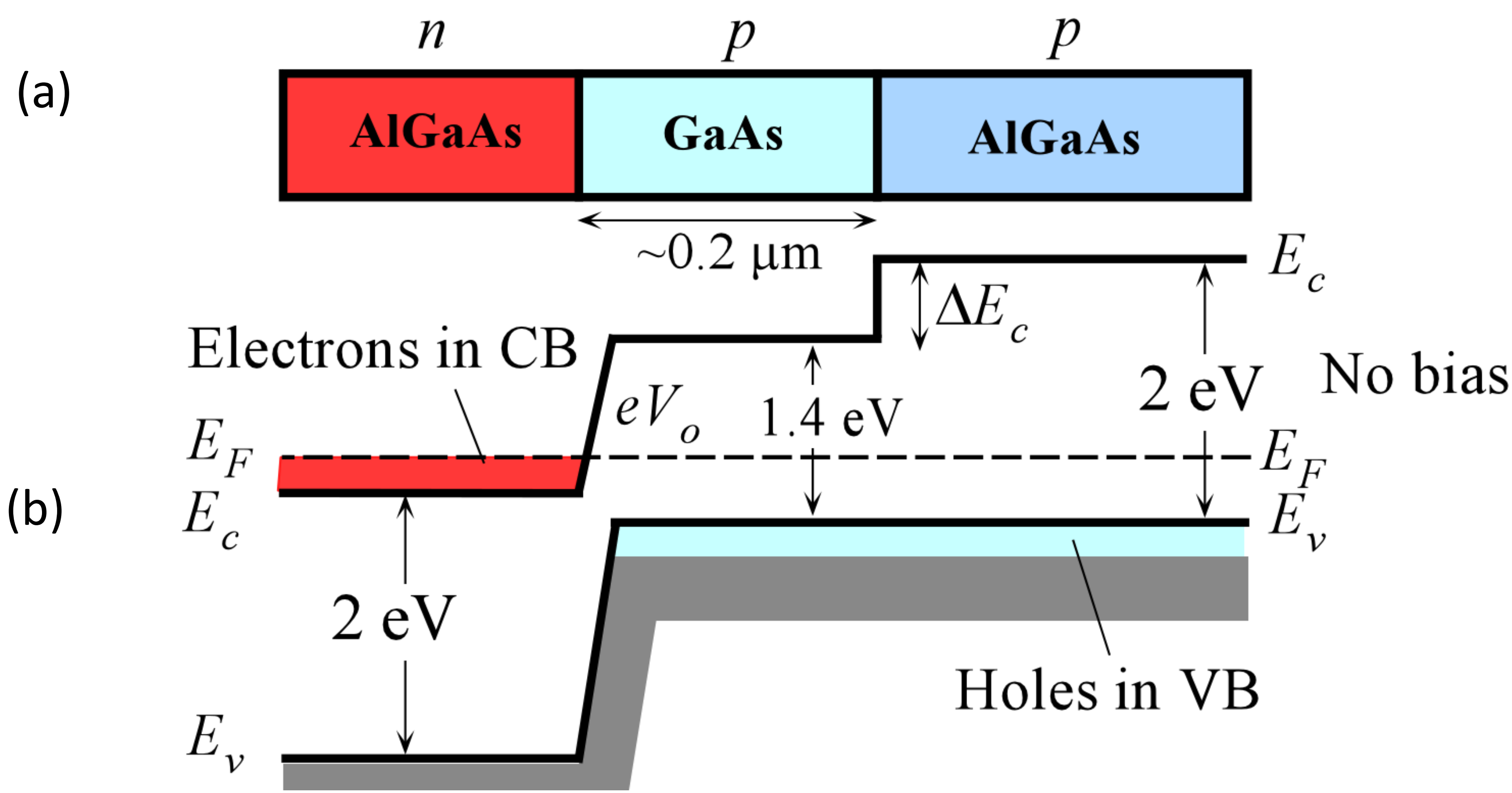
NOTE: Optical communication channels are at 850 nm (local network) and at 1.3 and 1.55 μm (long distance). D = direct bandgap, I = indirect bandgap. $\eta_{external}$ is typical and may vary substantially depending on the device structure. DH = double heterostructure, HJ = homojunction, QW = quantum well.

$$\eta_{external} = \frac{P_{out}(\text{optical})}{IV} \times 100\%$$

The external efficiency external of an LED quantifies the efficiency of conversion of electric energy into an emitted external optical energy

A Double Heterostructure Diode

A pn junction between two differently doped semiconductors that are of the same material, that is, the same bandgap (Eg) is called a **homojunction**. A junction between two different bandgap semiconductors is called a **heterojunction**. A semiconductor device structure that has junctions between different bandgap materials is called a **heterostructure device**.



(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs). (b) A simplified energy band diagram with exaggerated features. E_F must be uniform.

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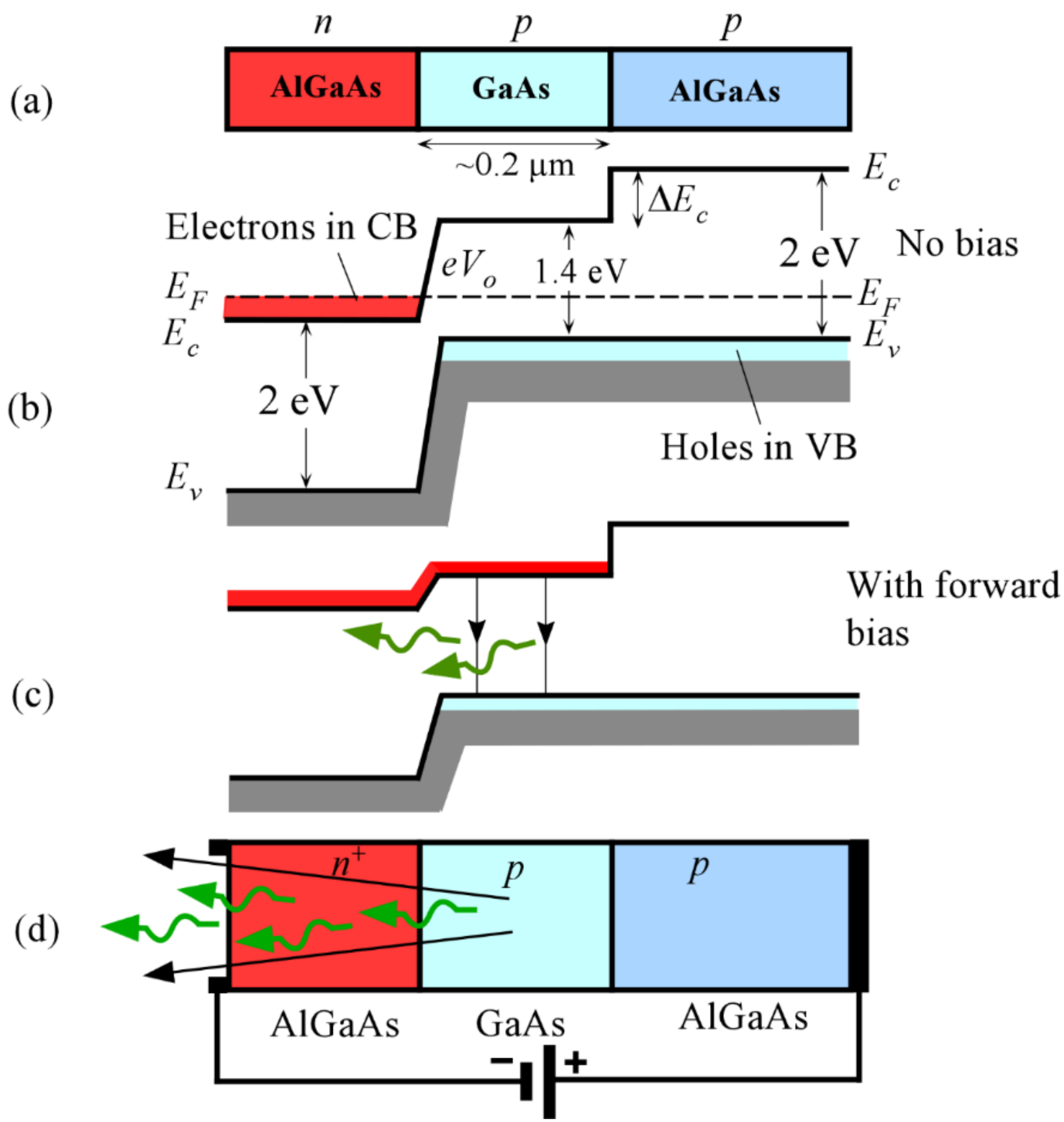
A Double Heterostructure Diode



(c) Forward-biased simplified energy band diagram. (d) Forward-biased LED. Schematic illustration of photons escaping reabsorption in the AlGaAs layer and being emitted from the device.

Applying forward bias reduces the potential barrier and injects electrons to GaAs layer. Electrons recombine with hole to cause spontaneous photon emission.

These electrons, however, are **confined** to the CB of GaAs since there is a barrier between GaAs and AlGaAs. The wide bandgap AlGaAs layers therefore act as **confining** layers that restrict injected electrons to the GaAs layer.

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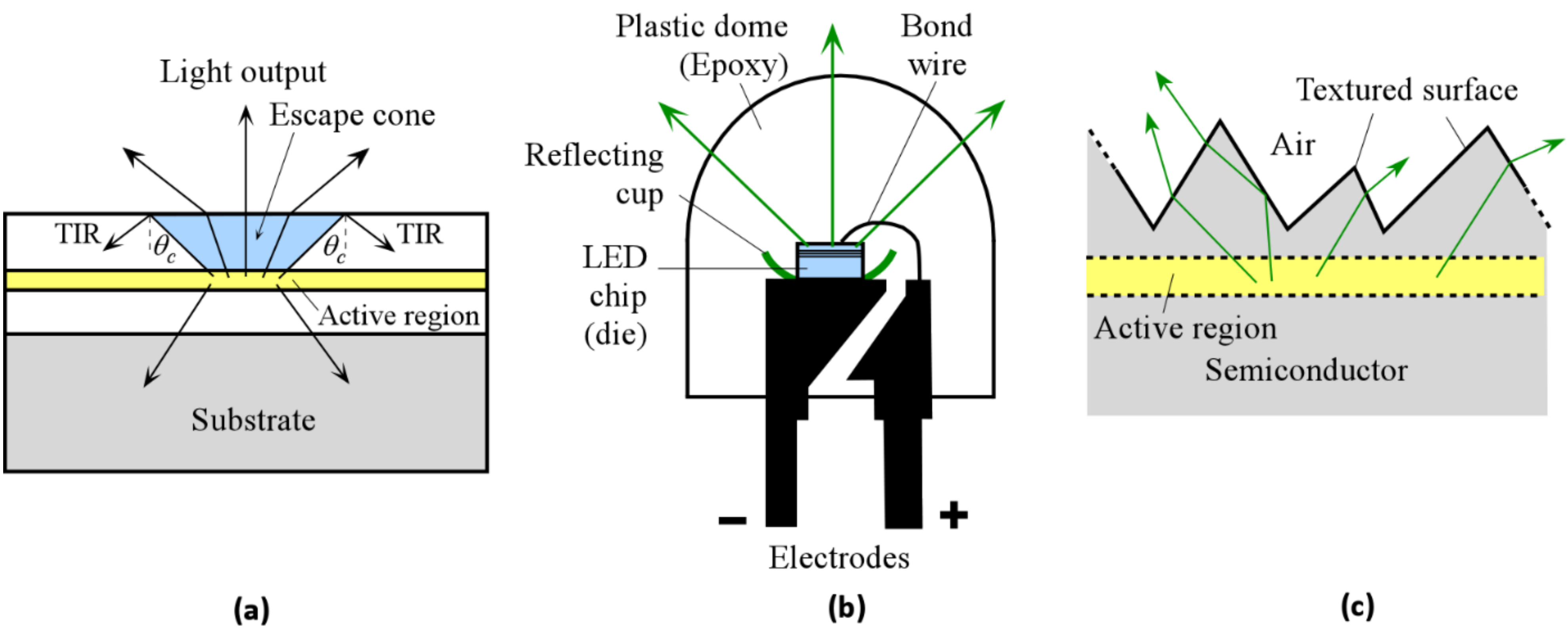
LED Extraction Efficiency



(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 center of a hemispherical plastic dome. (c) An example of a textured surface that allows light to escape after a couple of (or more) reflections (highly exaggerated sketch).

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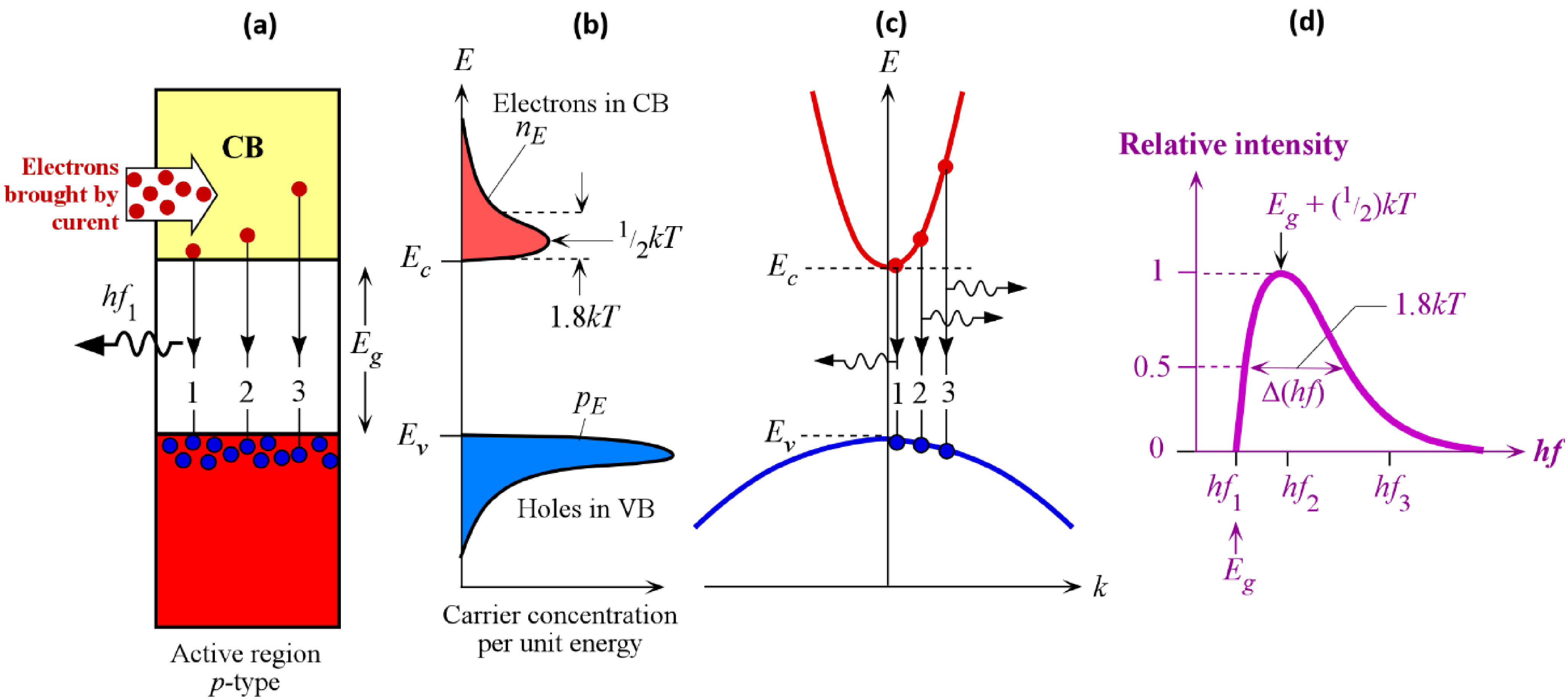
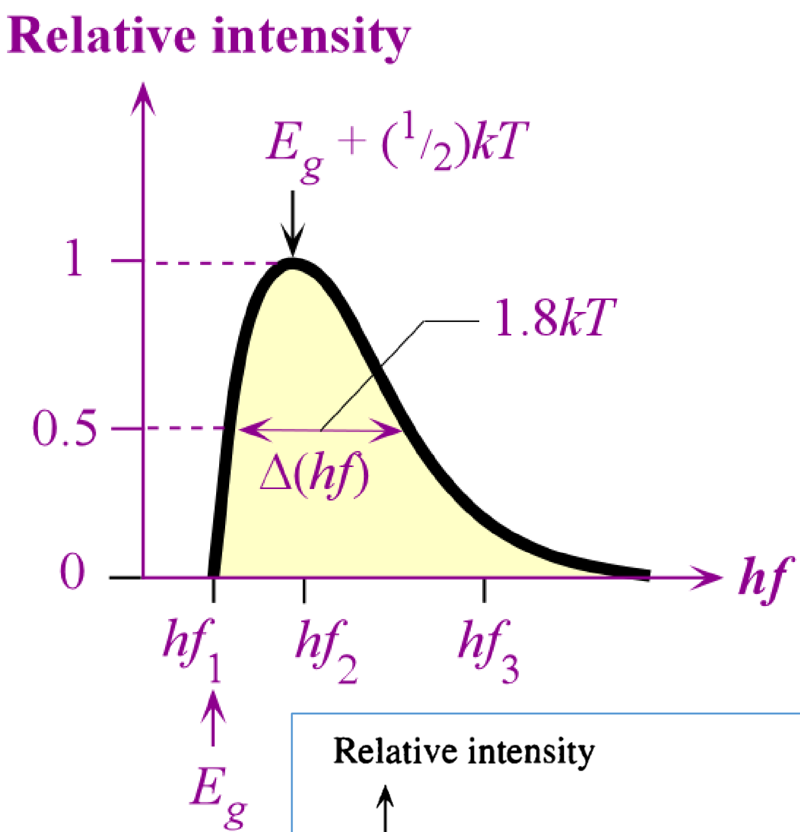
LED Emission Spectrum

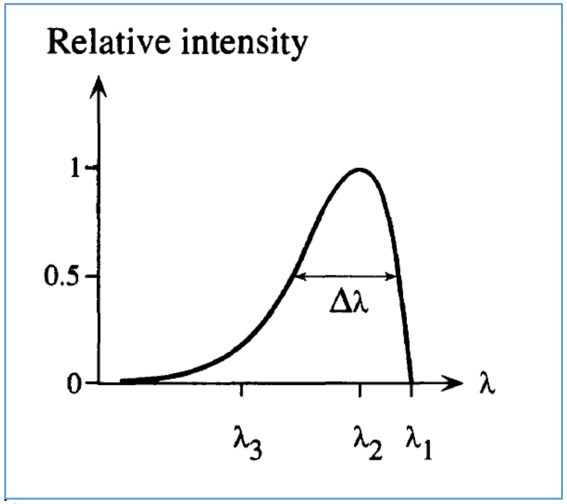
The electron concentration as a function of energy in the CB is given by g(E)f(E) where g(E) is the density of states and f(E) is the Fermi-Dirac function (probability of finding an electron in a state with energy E). The product g(E)f(E) represents the electron concentration per unit energy or the concentration in energy.



(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 $(1/2)kT$ above E_c. (c) A simplified E–k (equivalent to energy vs. momentum) diagram and direct recombination paths in which k (*i.e.* momentum) is conserved. (d) The relative light intensity as a function of photon energy based on (b) and (c)

LED Emission Spectrum





$$hf_o \approx E_g + \tfrac{1}{2}kT$$

$$h\Delta f = mkT$$

$m \approx 1.8$ (Theory)

Linewidth of the output spectrum is defined as the width between half-intensity points

$$\Delta\lambda = \lambda_o^2 \frac{mkT}{hc}$$

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Example

We know that a spread in the output wavelengths is related to a spread in the emitted photon energies. The emitted photon energy $E_{ph} = hc/\lambda$ and the spread in the photon energies $\Delta E_{ph} = \Delta(hv) = mkT$ between the half intensity points as shown in previous figure. Show that the corresponding linewidth between the half-intensity points in the output spectrum is:

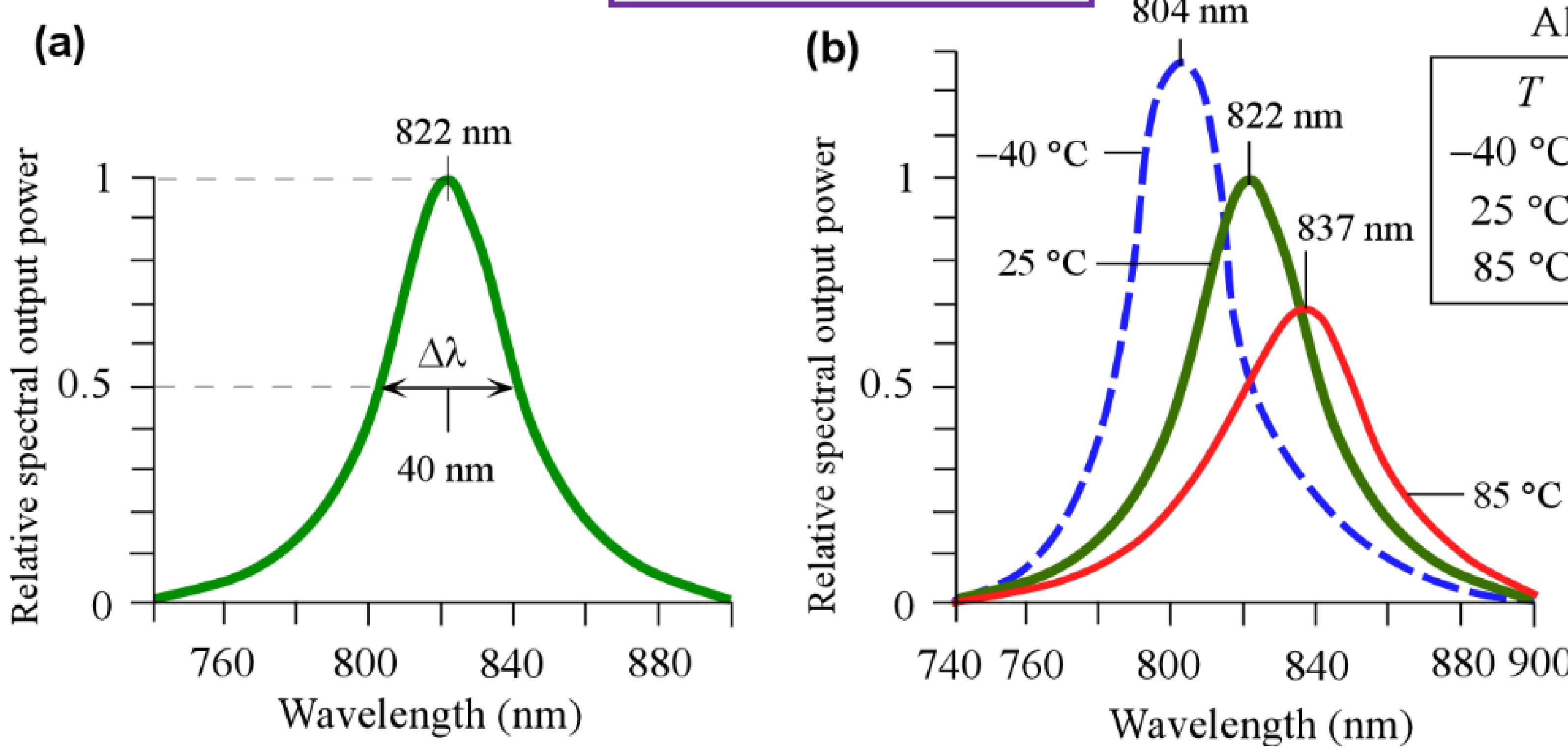
$$\boxed{\Delta\lambda = \lambda_o^2 \frac{mkT}{hc}}$$

What is the spectral linewidth of an optical communications LED operating at 1550 nm and at 300 K?

3002 Electronic Devices
R. Ghannam

LED Emission Spectrum

$$\Delta\lambda = \lambda_o^2 \frac{mkT}{hc}$$



AlGaAs IR LED

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

(a) A typical output spectrum (relative spectral intensity versus 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 full width at half maximum (between half intensity points).

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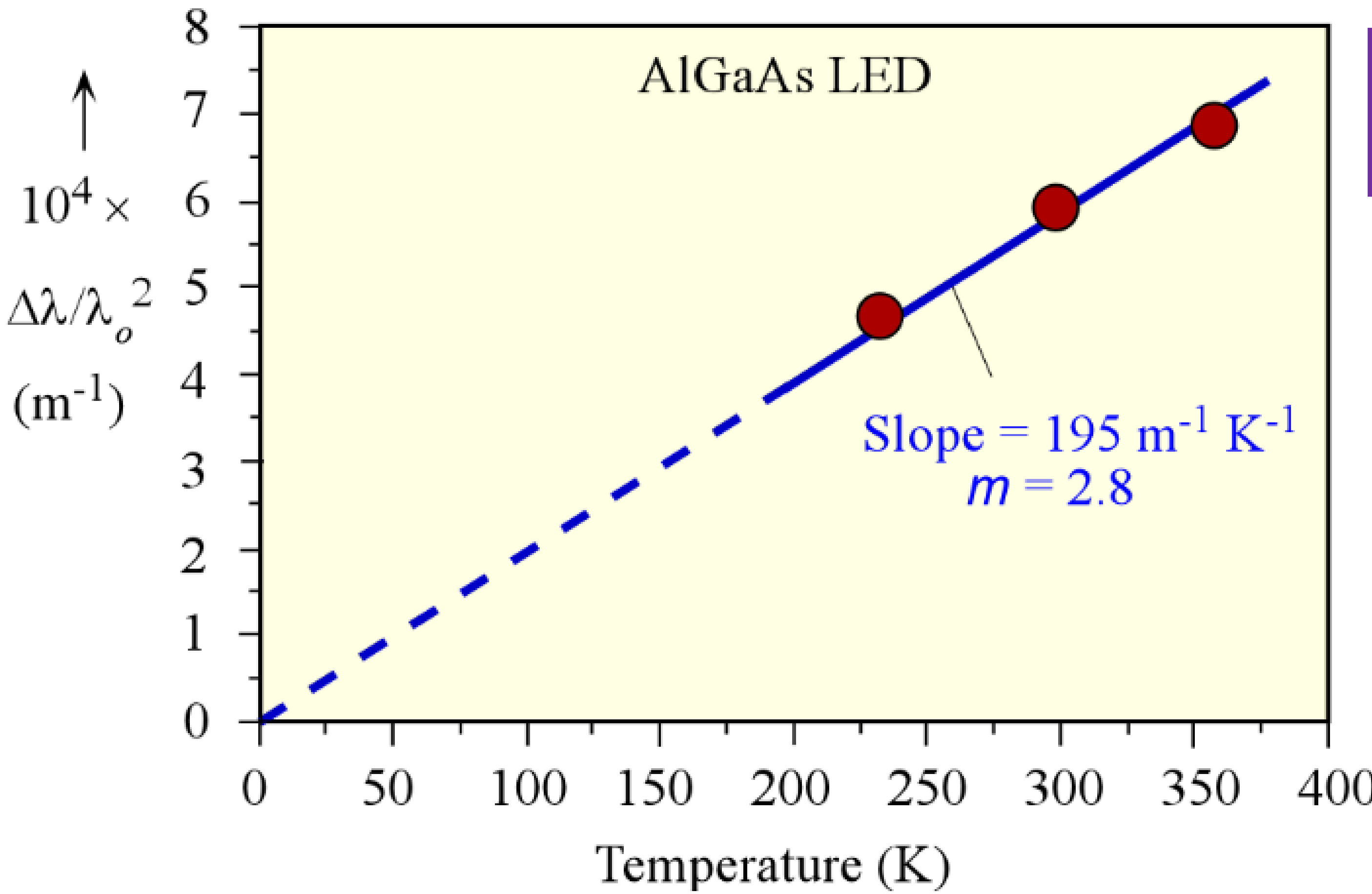
LED Spectral Width vs Temperature



$$\Delta\lambda = \lambda_o^2 \frac{mkT}{hc}$$

The plot of plot $\Delta\lambda/\lambda_o^2$ vs. T for an AlGaAs infrared LED, using the peak wavelength λ_o and spectral width $\Delta\lambda$ at three different temperatures,

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Power Conversion Efficiency

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

$$\eta_{\mathrm{PCE}} = \frac{\text{Optical output power}}{\text{Electrical input power}} = \frac{P_o}{IV}$$