Semiconductor Optoelectronics – Lecture 14

General principles

Photodetectors: p-n and p-i-n diodes

Solar cells

Light Emitting Diodes and Laser Diodes

References other than your book, Singh

1. S.O.Kasap, Optoelectronics and Photonics, Principles and Practices, Prentice-Hall International, NJ, USA, 2001.
2. S.M.Sze, Semiconductor Devices, Physics and Technology, 2nd edition, John Wiley & Sons, Inc., NY, USA, 2002.
3. Jenny Nelson, The physics of solar cells, Imperial College Press, London, 2003

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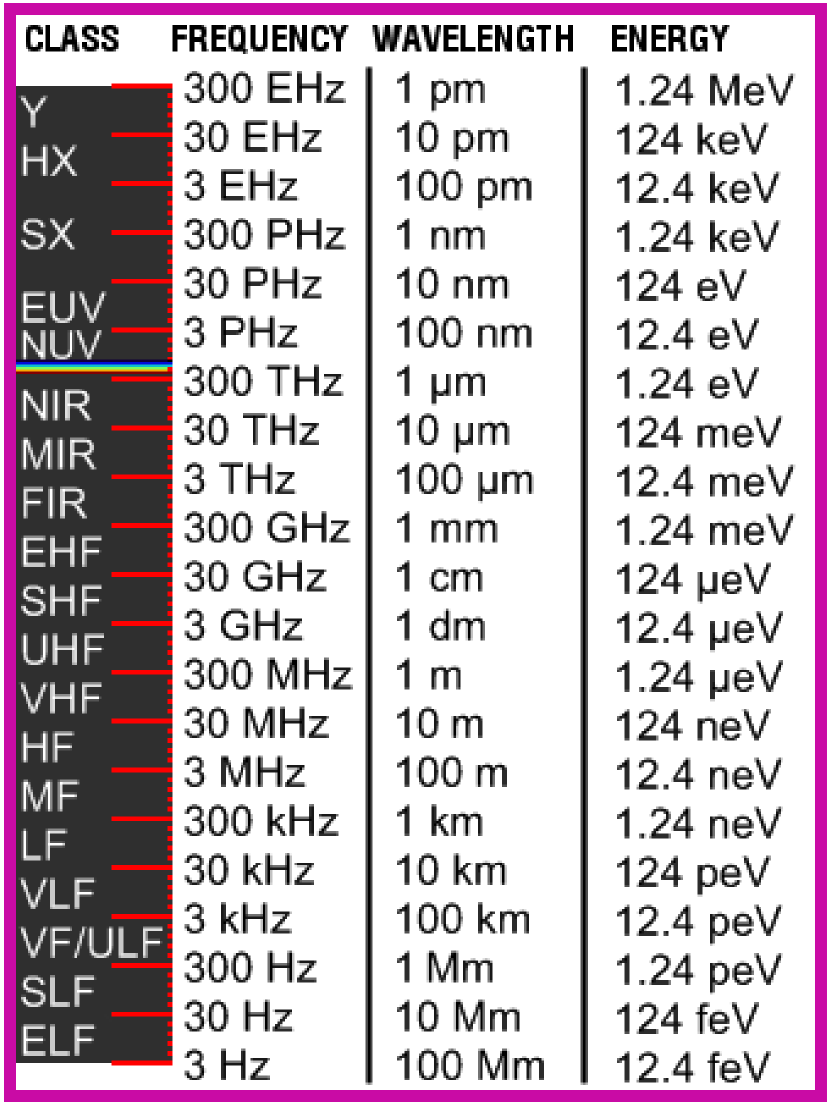
Electromagnetic spectrum (1)



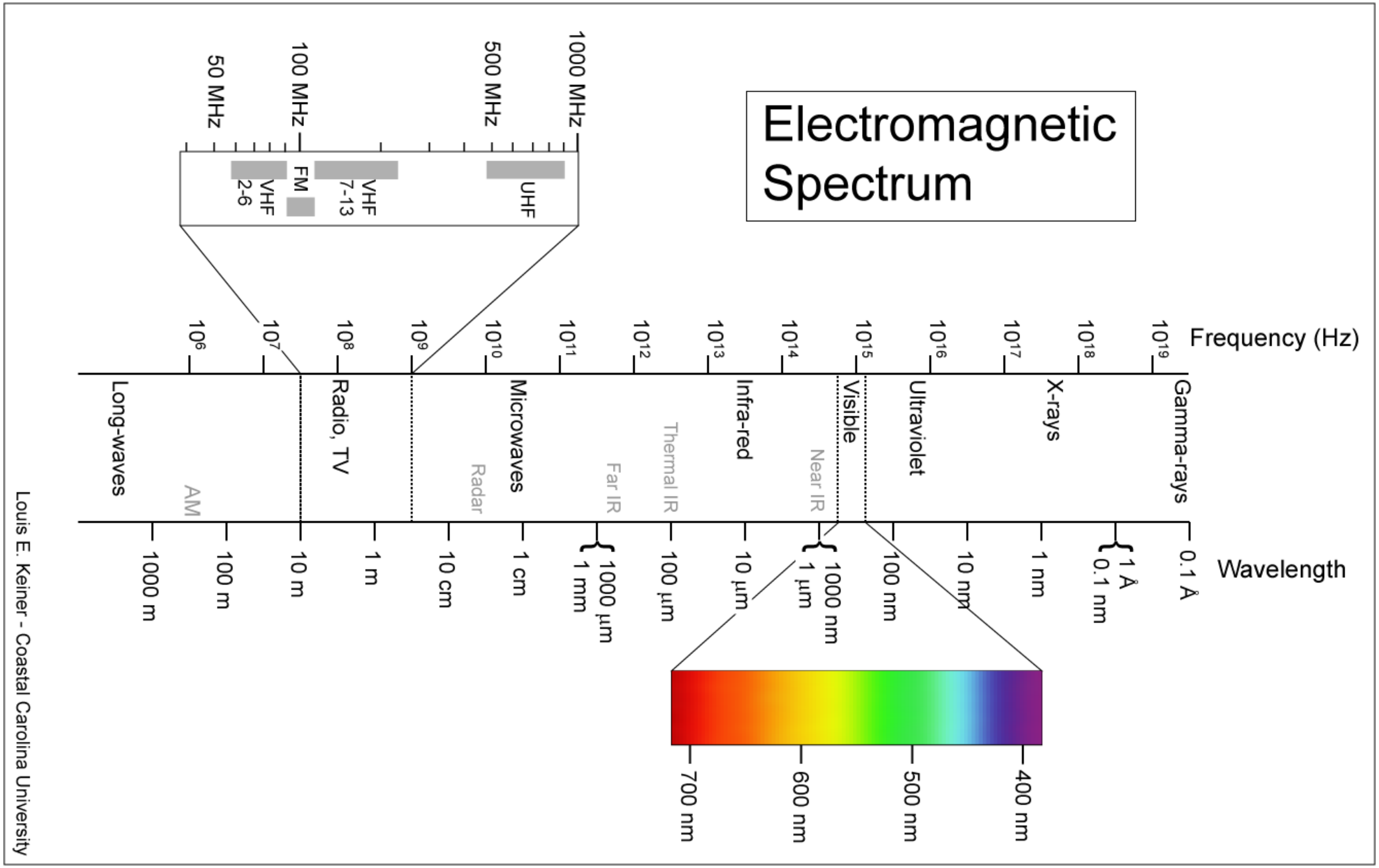
CLASS	FREQUENCY	WAVELENGTH	ENERGY
Y	300 EHz	1 pm	1.24 MeV
HX	30 EHz	10 pm	124 keV
SX	3 EHz	100 pm	12.4 keV
	300 PHz	1 nm	1.24 keV
EUV	30 PHz	10 nm	124 eV
NUV	3 PHz	100 nm	12.4 eV
NIR	300 THz	1 µm	1.24 eV
MIR	30 THz	10 µm	124 meV
FIR	3 THz	100 µm	12.4 meV
EHF	300 GHz	1 mm	1.24 meV
SHF	30 GHz	1 cm	124 µeV
UHF	3 GHz	1 dm	12.4 µeV
VHF	300 MHz	1 m	1.24 µeV
HF	30 MHz	10 m	124 neV
MF	3 MHz	100 m	12.4 neV
LF	300 kHz	1 km	1.24 neV
VLF	30 kHz	10 km	124 peV
VF/ULF	3 kHz	100 km	12.4 peV
SLF	300 Hz	1 Mm	1.24 peV
ELF	30 Hz	10 Mm	124 feV
	3 Hz	100 Mm	12.4 feV

Legend

Y = Gamma rays
HX = Hard X-rays
SX = Soft X-rays
EUV = Extreme ultraviolet
NUV = Near ultraviolet visible light
NIR = Near infrared
MIR = Mid infrared
FIR = Far infrared   radiowaves
EHF = Extremely high frequency
SHF = Super high frequency
UHF = Ultra high frequency
VHF = Very high frequency
HF = High frequency
MF = Medium frequency
LF = Low frequency
VLF = Very low frequency
VF/ULF = Voice frequency
SLF = Super low frequency
ELF = Extremely low frequency

From Wikipedia

Electromagnetic spectrum (2)

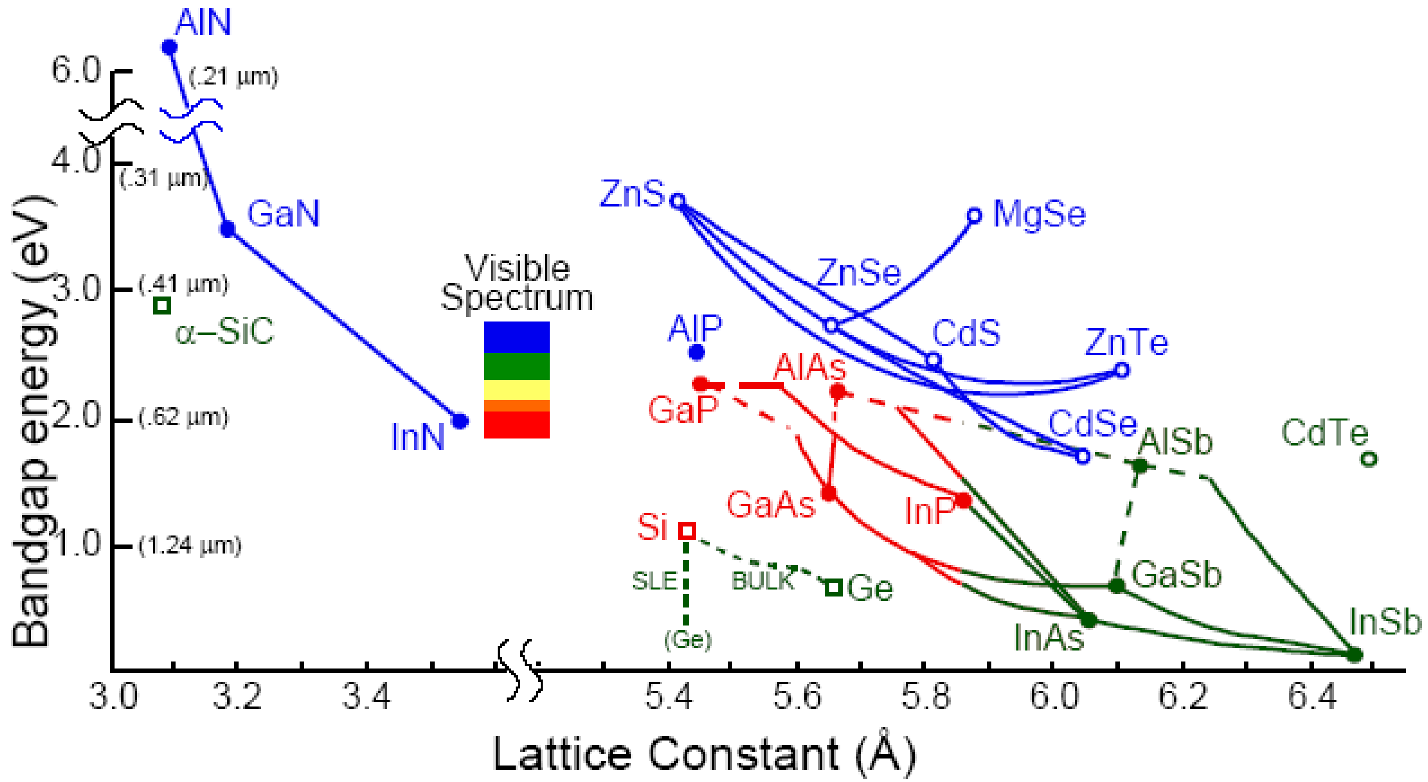


Louis E. Keiner - Coastal Carolina University

From Wikipedia

Which wavelength do you want?

Here is the smörgåsbord of the materials for the wavelength of your choice!



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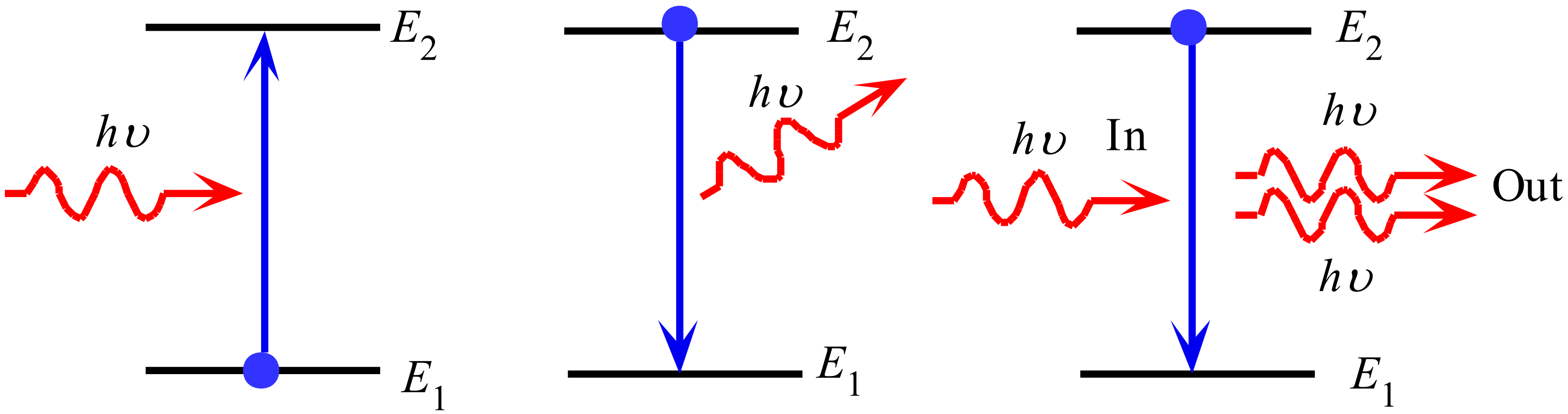
Solar cells, detectors

Light emitting diodes

Laser diodes



(a) Absorption (b) Spontaneous emission (c) Stimulated emission

Absorption, spontaneous (random photon) emission and stimulated emission.

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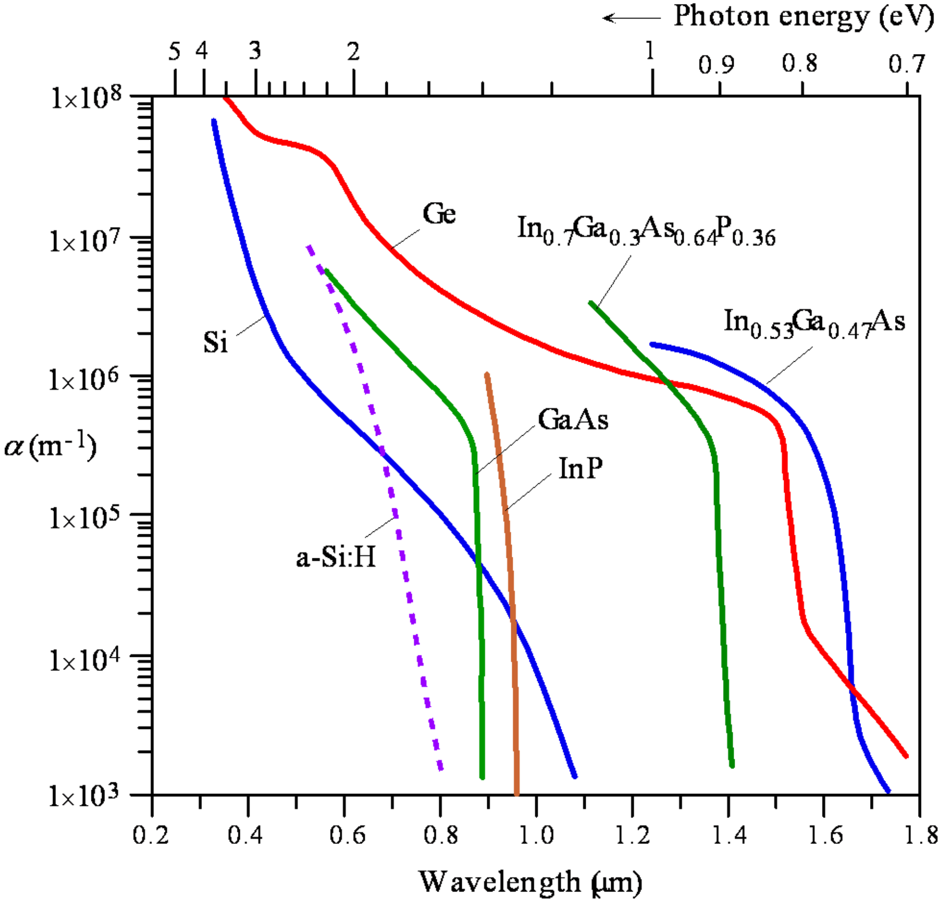
DETECTORS

Absorption coefficient, an important parameter for detectors



Absorption coefficient (α) vs. wavelength (λ) for various semiconductors
(Data selectively collected and combined from various sources.)

Figure 5.3

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Source: Kasap

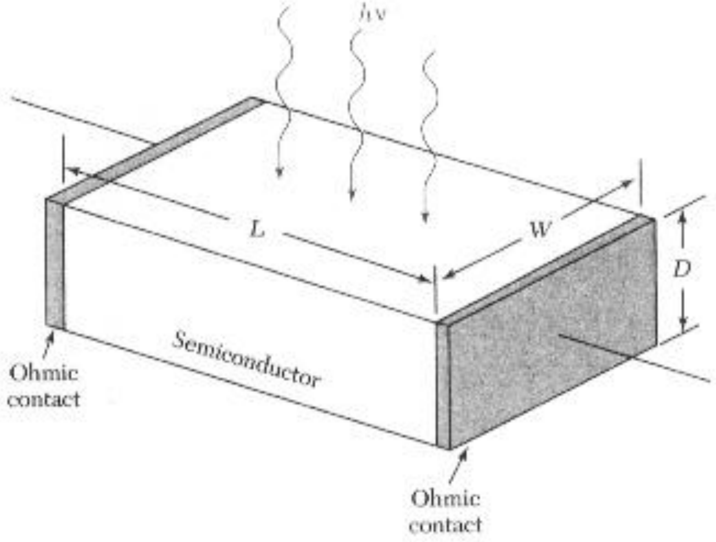


Fig. 30 Schematic diagram of a photoconductor that consists of a slab of semiconductor and two contacts at the ends.

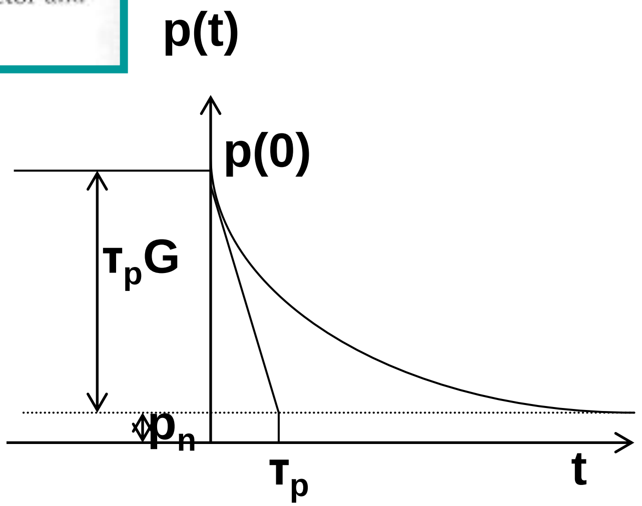
<u>At equilibrium</u>

G, Generation rate of e-h pairs ($m^{-3}\ s^{-1}$)

$= \alpha\ J_{ph}(x)$

$= n/\tau =$ recombination rate

(n= no. of pairs/volume; τ = recombination life time)



Decay of minority carriers (holes) with time in n-type semiconductor

Source: Sze

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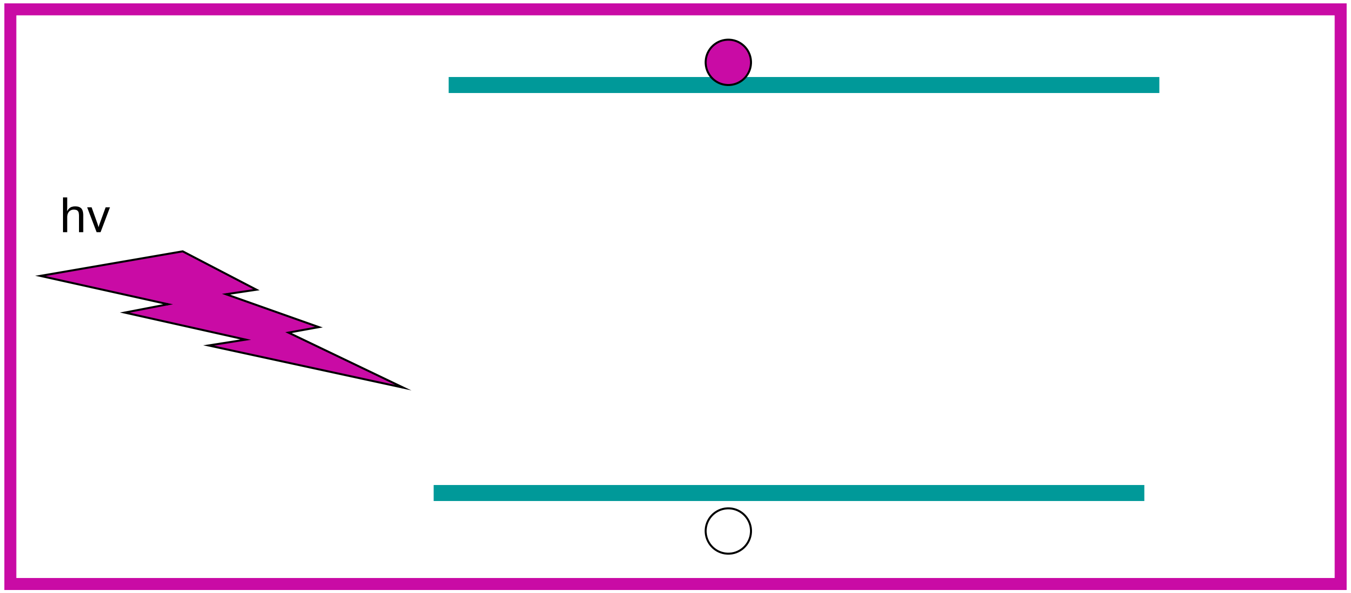
Photodetector



Detector :

Conductivity change due to e-h pair generation

Generation of a voltage signal

No field? e-h pairs are useless since they will recombine; hence use an applied field or make use of a p-n junction’s built-in field!

p-n diode

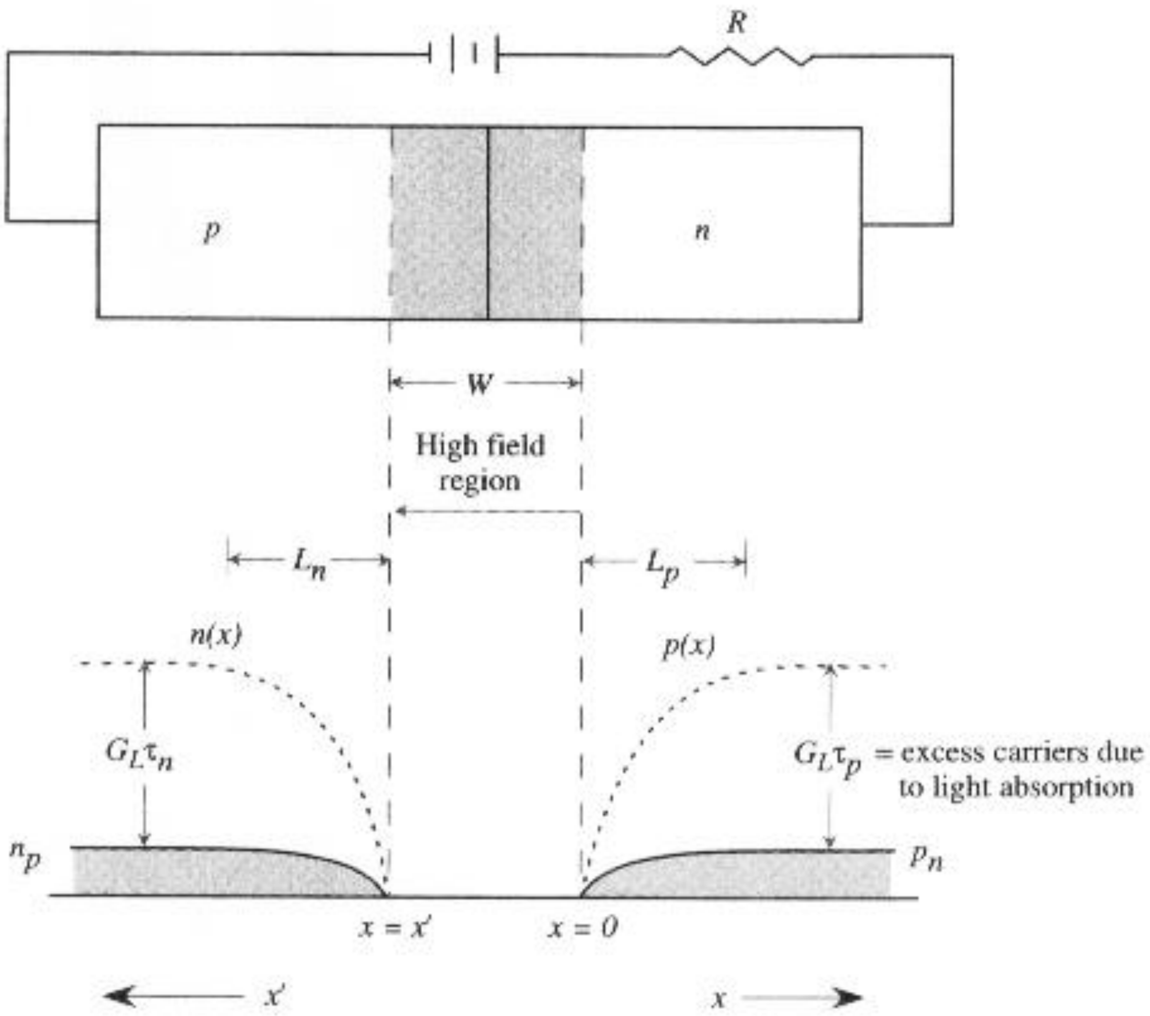


Figure 11.5: A schematic of a *p*-*n* diode and the minority carrier concentration in absence and presence of light. The minority charge goes to zero at the depletion region edge due to the high field, which sweeps the charge away. The equilibrium minority charge is p_n and n_p in the *n*- and *p*-sides, respectively.

Source: Singh

Total current in a photodiode =

Current in the depletion region (prompt current)

+

Currents in the neutral region

+

Dark current

Remember:

The photocurrent direction is in the direction of the reverse current of the diode

R_{ph}, Responsivity of a detector (A/W)

= Current density/Optical Intensity

= $(I_L/\text{Area})/(\text{W}/\text{area}) = J_L/P_{op}$

L represents total active length of the detector

= Depletion width + $L_n + L_p$

η, Quantum efficiency (carriers collected per photon)

= $(J_L/e)/(P_{op}/\hbar\omega)$

= $R_{ph}\ (\hbar\omega/e)$

P-I-N DIODE

Need for the P-I-N diode:

- P-N diode limited by reverse current breakdown; use i-region
- i-region completely depleted = Large depletion region

=> Large prompt current = high frequency and high quantum efficiency

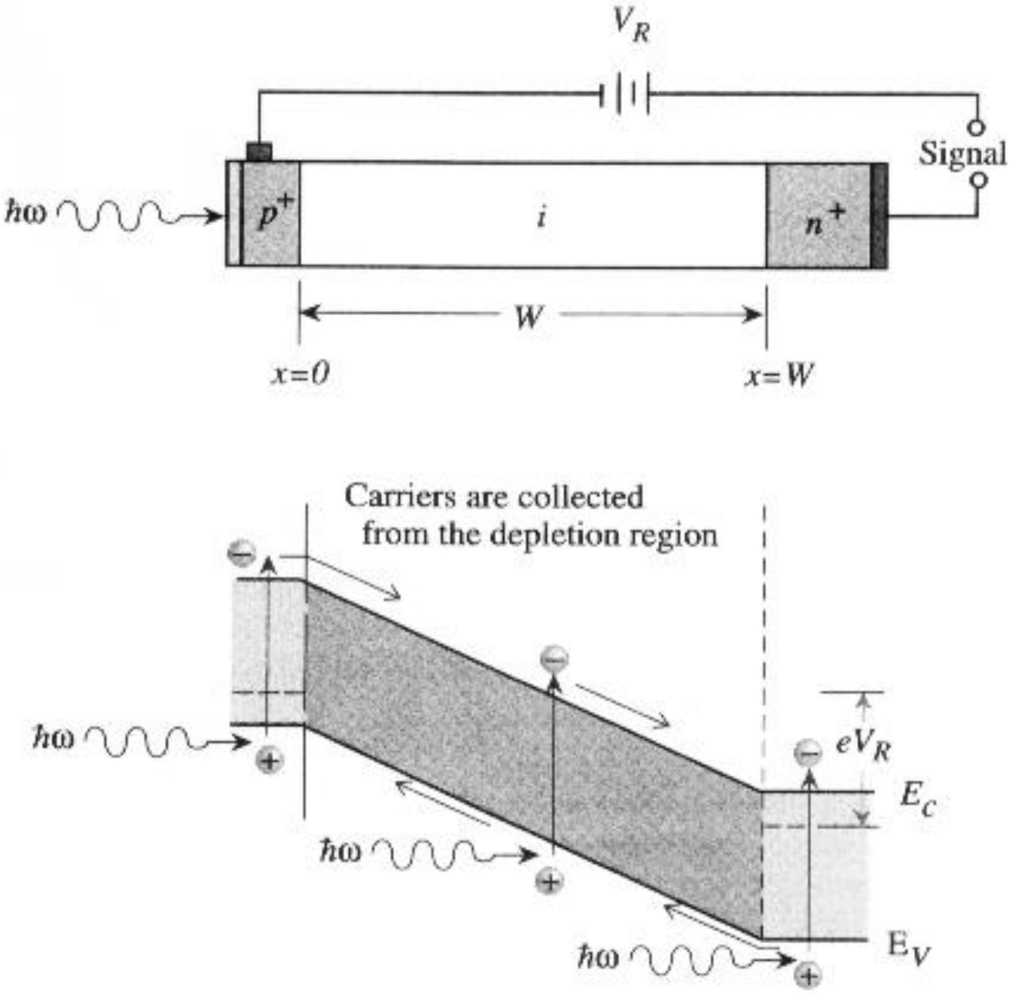


Figure 11.9: A cross-section and energy band profile of a *p-i-n* detector structure. Carriers generated in the depletion region are collected and contribute to the current. If the intrinsic region is thick, the photocurrent is dominated by carriers collected from the depletion region, since the carriers generated in the neutral regions contribute a smaller fraction of photocurrent. Since the photocurrent is dominated by the prompt photocurrent, the device response is fast.

SOLAR CELLS

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SOLAR CELLS

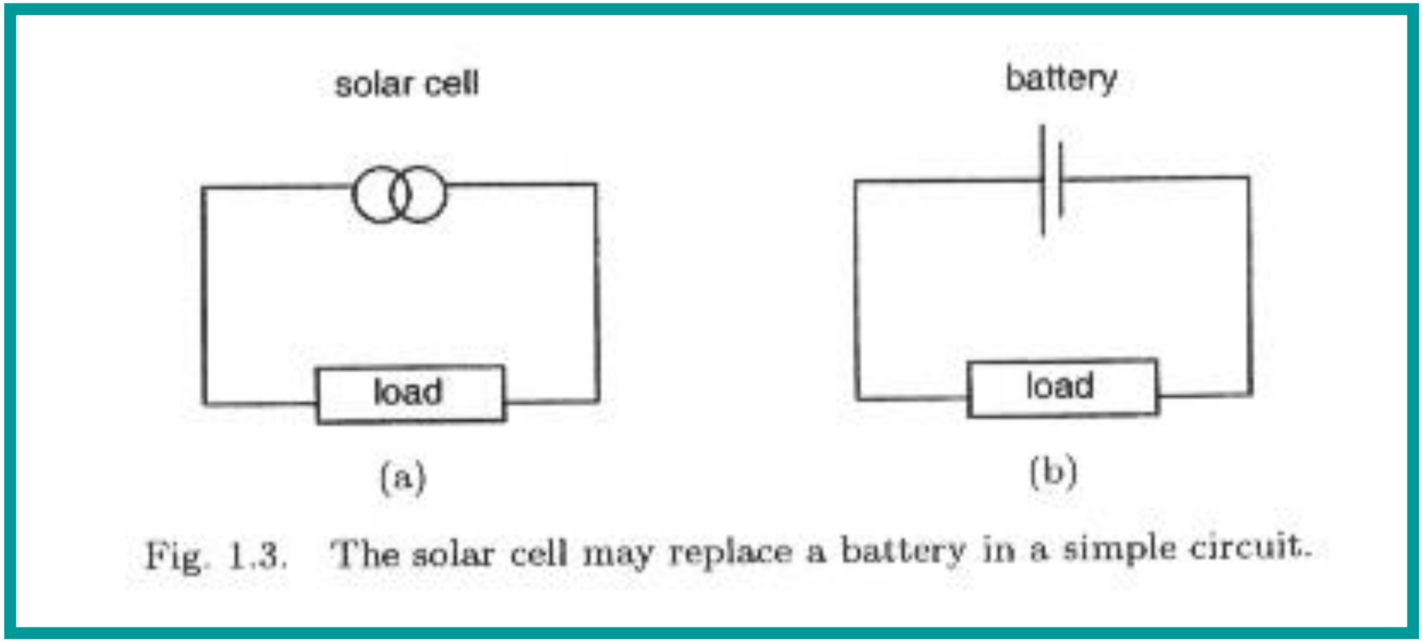

Fig. 1.3. The solar cell may replace a battery in a simple circuit.

Source: Nelson

Dark? Nothing happens in (a)

Illuminated? Behaves like (b) as if there is a battery
Two extreme cases:
*** Terminals isolated (open circuit, oc) = Infinite load resistance:**
$V = V_{oc}$ and $I = 0$
*** Terminals closed (short circuit, sc) = zero load resistance:**
$V = 0$ and $I = I_{sc}$
For any intermediate load resistance, R_L, the cell develops a voltage 0- V_{oc} and current I such that $I = V/ R_L$

- Battery = voltage generator
- Solar cell = current generator

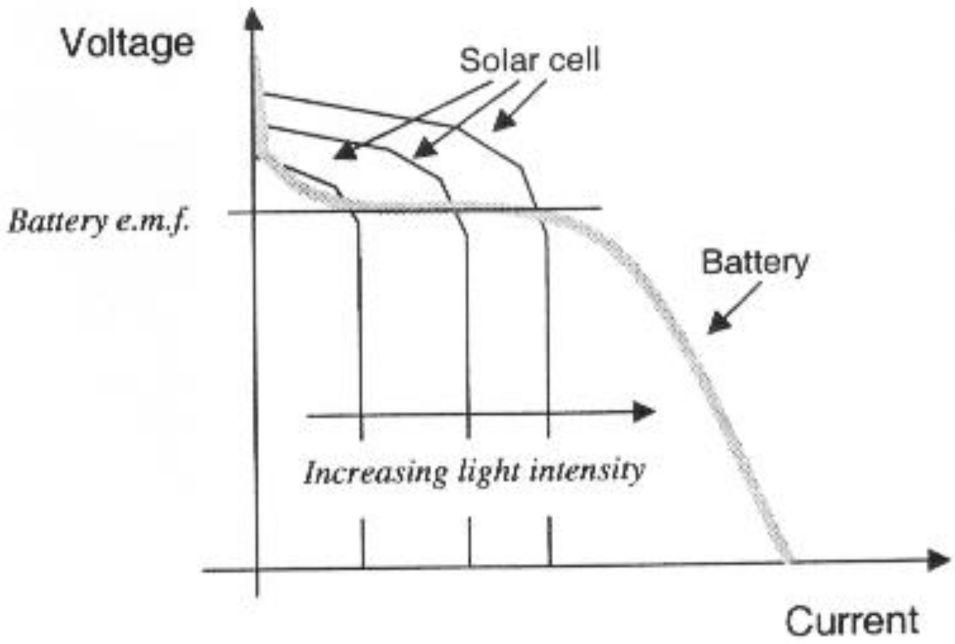

Fig. 1.4. Voltage–current curves of a conventional battery (grey) and a solar cell under different levels of illumination. A battery normally delivers a constant e.m.f. at different levels of current drain except for very low resistance loads, when the e.m.f. begins to fall. The battery e.m.f. will also deteriorate when the battery is heavily discharged. The solar cell delivers a constant current for any given illumination level while the voltage is determined largely by the resistance of the load. For photovoltaic cells it is usual to plot the data in the opposite sense, with current on the vertical axis and voltage on the horizontal axis. This is because the photovoltaic cell is essentially a current source, while the battery is a voltage source.

Source: Nelson

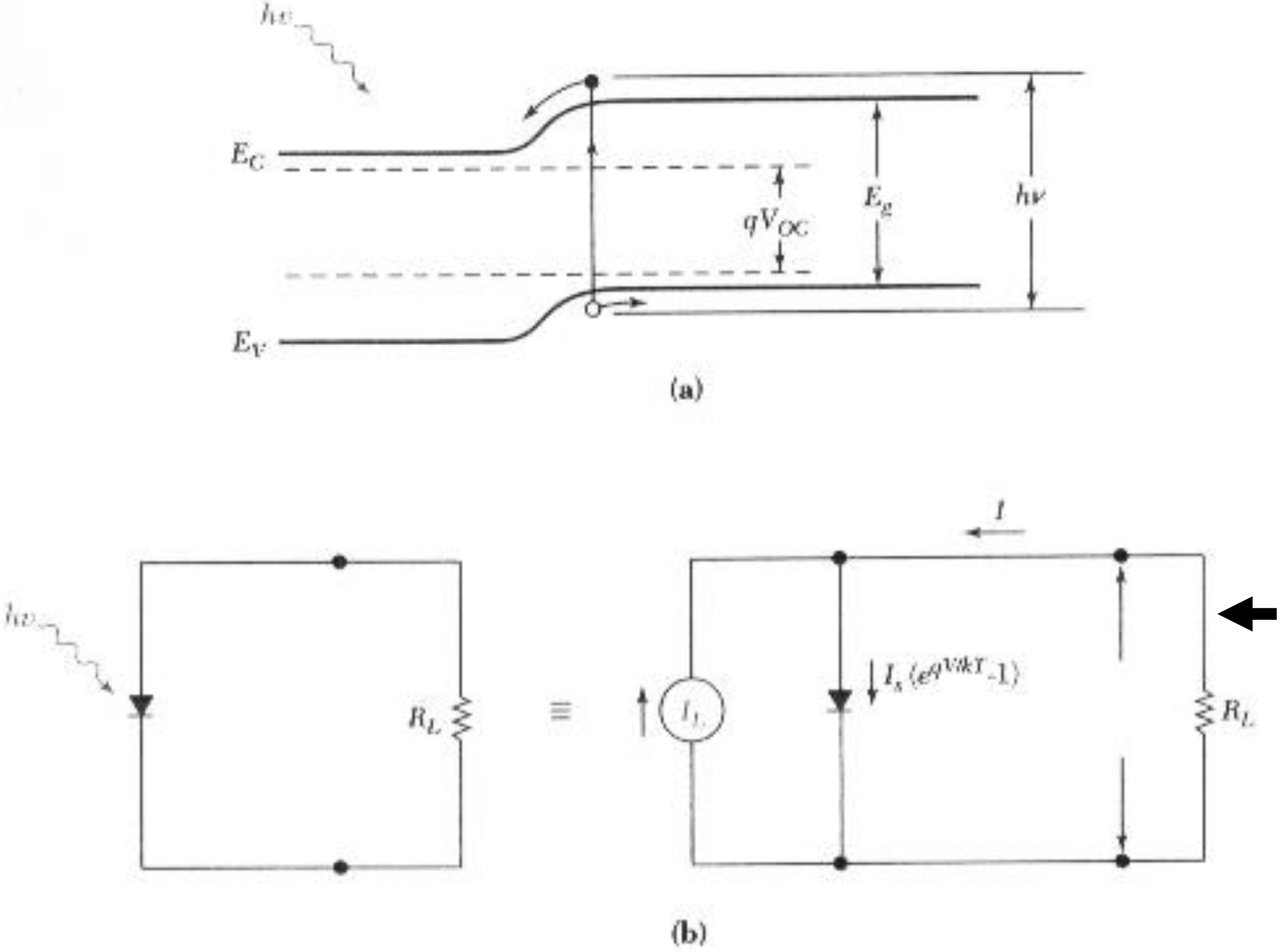

Fig. 37 (*a*) Energy band diagram of a *p–n* junction solar cell under solar irradiation. (*b*) Idealized equivalent circuit of a solar cell.

Constant curent source I_L in parallel with the junction

I_L = Current resulting from solar radiation; I_s = Saturation current

Source: Sze

Ideal I-V curve of the device in the previous slide:

$I = I_s\,[\exp(eV/kT)-1] - I_L$ where I_s is expressed as

$$J_s = \frac{I_s}{A} = eN_C N_V \left(\frac{1}{N_A}\sqrt{\frac{D_n}{\tau_n}} + \frac{1}{N_D}\sqrt{\frac{D_p}{\tau_p}} \right) \exp(-E_g / kT)$$

Plot of I vs. V gives the curve in the next slide

Source: Nelson

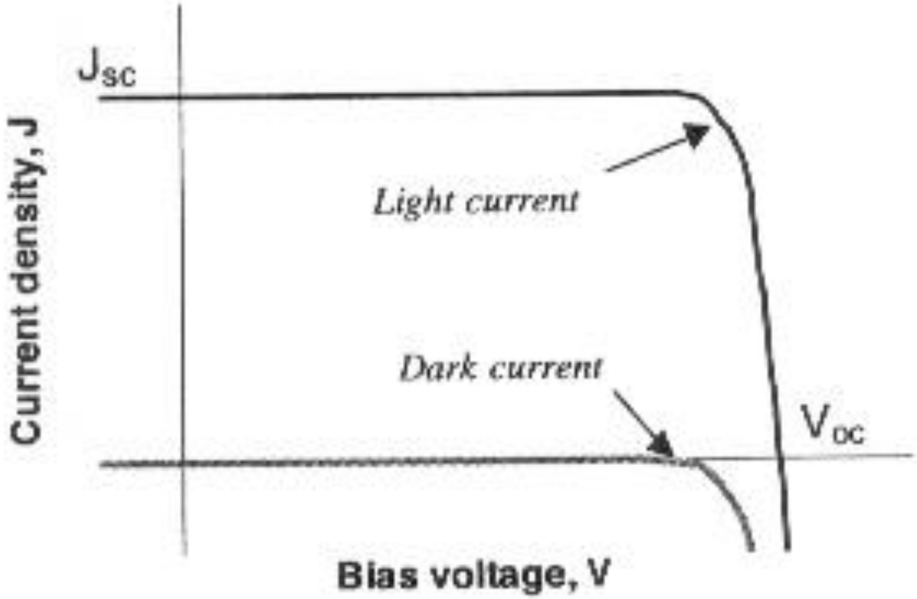

Fig. 1.6. Current–voltage characteristic of ideal diode in the light and the dark. To a first approximation, the net current is obtained by shifting the bias dependent dark current up by a constant amount, equal to the short circuit photocurrent. The sign convention is such that the short circuit photocurrent is positive.

Source: Nelson

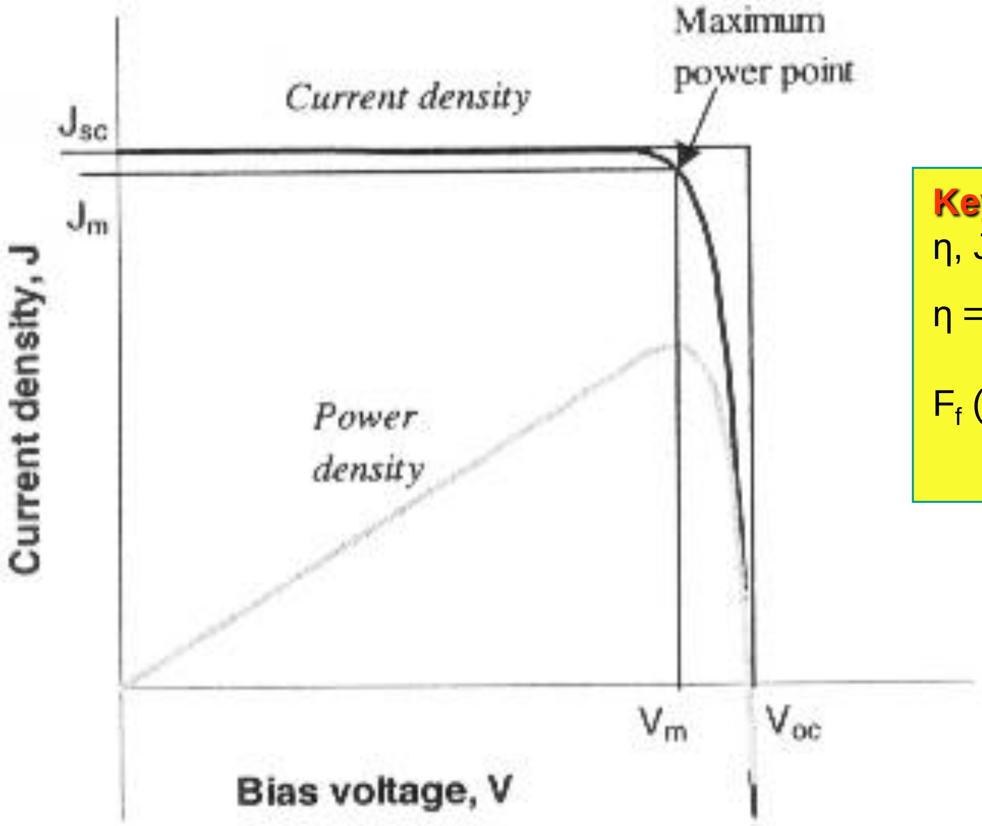

Fig. 1.8. The current voltage (black) and power–voltage (grey) characteristics of an ideal cell. Power density reaches a maximum at a bias V_m, close to V_{oc}. The maximum power density $J_m \times V_m$ is given by the area of the inner rectangle. The outer rectangle has area $J_{sc} \times V_{oc}$. If the fill factor were equal to 1, the current voltage curve would follow the outer rectangle.

Key parameters:

η, J_{sc}, V_{oc} and F_f

$\eta = P_m/P_{in} = I_m V_m/P_{in}$

F_f (fill factor) = $I_m V_m/I_{sc} V_{oc}$

Source: Nelson

Certain Facts, Definitions and Standard Test Conditions for Photovoltaics

- Nuclear fusion of 6×10^{11} kg of hydrogen into helium takes place every second in the sun
- Net mass loss = 4×10^{3} kg = Energy that is radiated by sun every second = 4×10^{20} J ($E = mc^2$)
- This energy primarily in the ultra violet to infrared region (0.2 – 3 µm)

- Solar constant = Intensity of solar radiation outside the earth's atm. at its average distance of its orbit around the sun = 1367 W/m^2
- But the solar radiation is absorbed or scattered when it enters the earth's atmosphere
- The attenuation depending on the air mass or the path the solar radiation has transversed
- Air mass (AM) = 1/cos θ, where θ is the angle between the vertical and the sun's position
- Air mass conveniently calculated as $\sqrt{1+(s/h)^2}$ s = shadow length of an object of height = h

- AM1.5 spectrum at an incident power density of 963 Wm^{-2}
- AM1.5= Air mass 1.5 spectrum = Spectrum representing the sunlight at the earth's surface when the sun is at an angle of 48^o from the vertical
- AM1.0 = Radiation when the sun is at vertical position
- AM0 = Radiation outside the earth's atmosphere

Source: Sze

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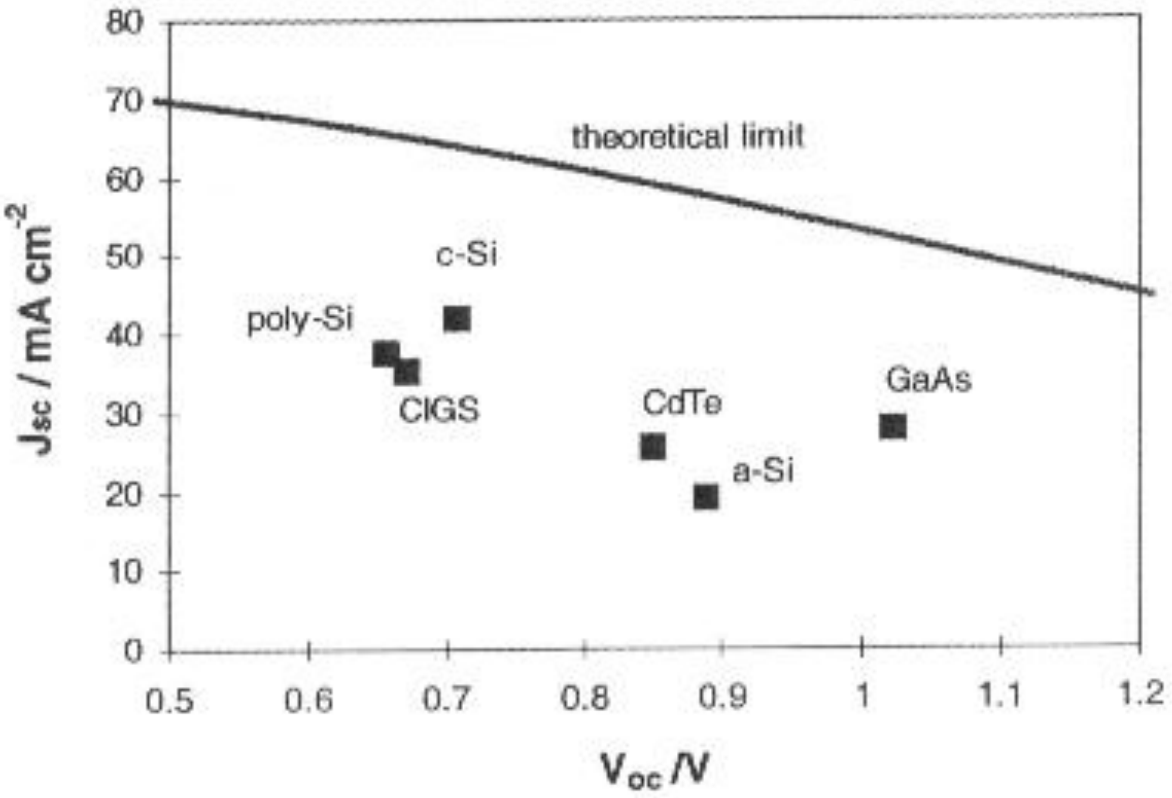


Fig. 1.9. Plot of J_{sc} against V_{oc} for the cells listed in Table 1.1. Materials with high V_{oc} tend to have lower J_{sc}. This is due to the band gap of the semiconductor material. The grey line shows the relationship expected in the theoretical limit.

Source: Nelson

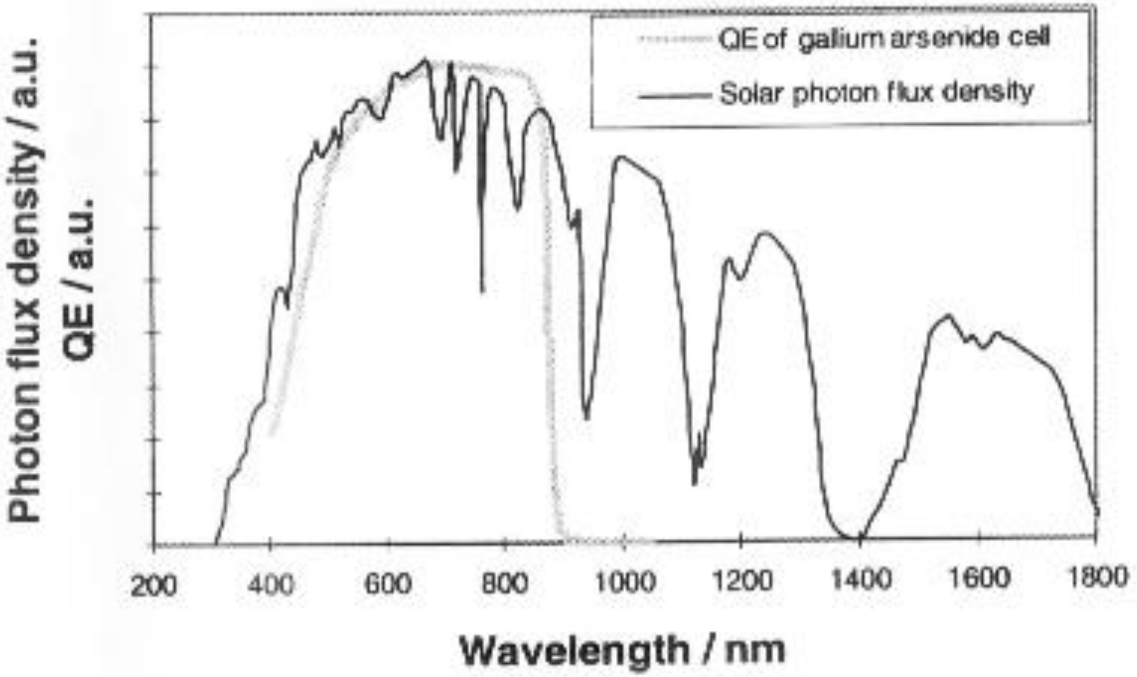


Fig. 1.5. Quantum efficiency of GaAs cell compared to the solar spectrum. The vertical scale is in arbitrary units, for comparison. The short circuit photocurrent is obtained by integrating the product of the photon flux density and QE over photon energy. It is desirable to have a high QE at wavelengths where the solar flux density is high.

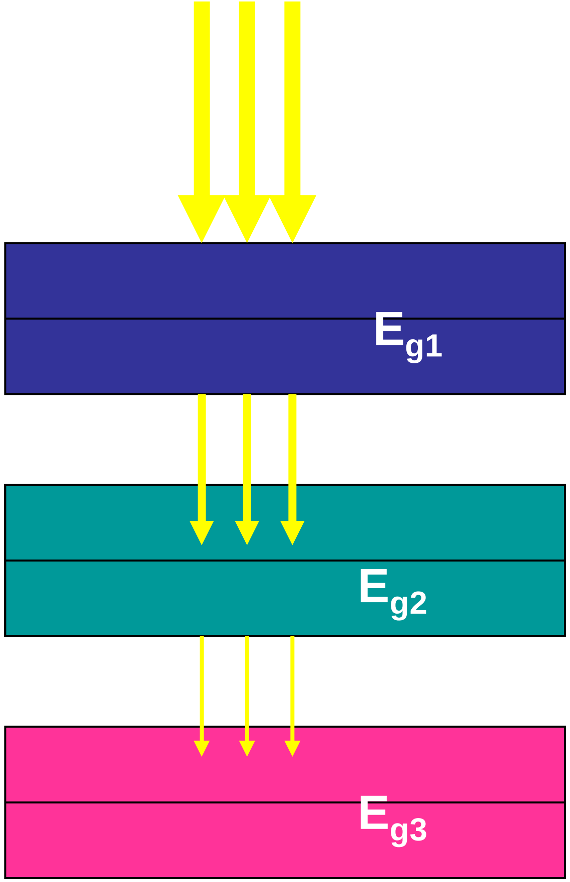
Source: Nelson

Increasing the efficiency

Multiple junction or Tandem solar cells:

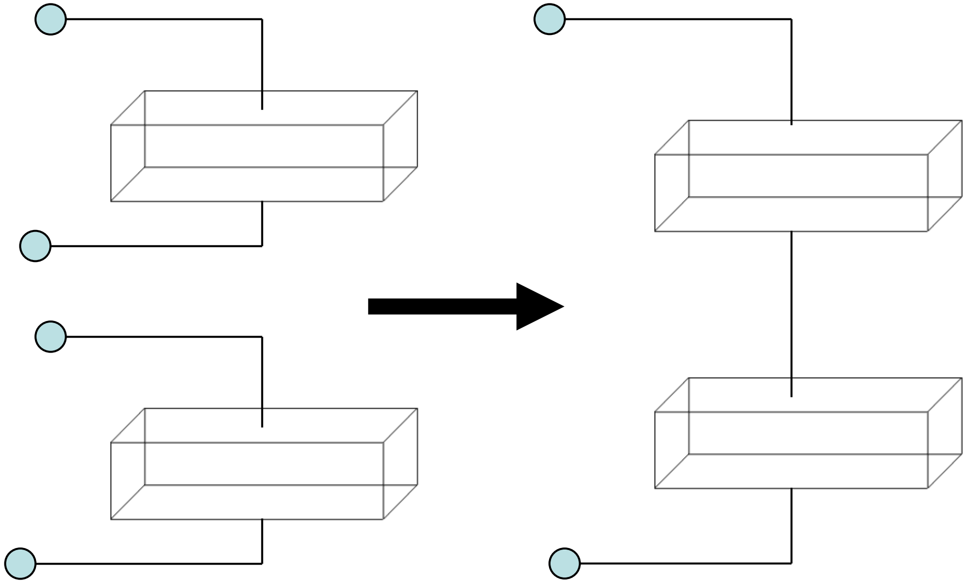
- Two or more bandgaps together
- Light not absorbed in high bandgap material will be absorbed in the low bandgap material

=> Increased efficiency

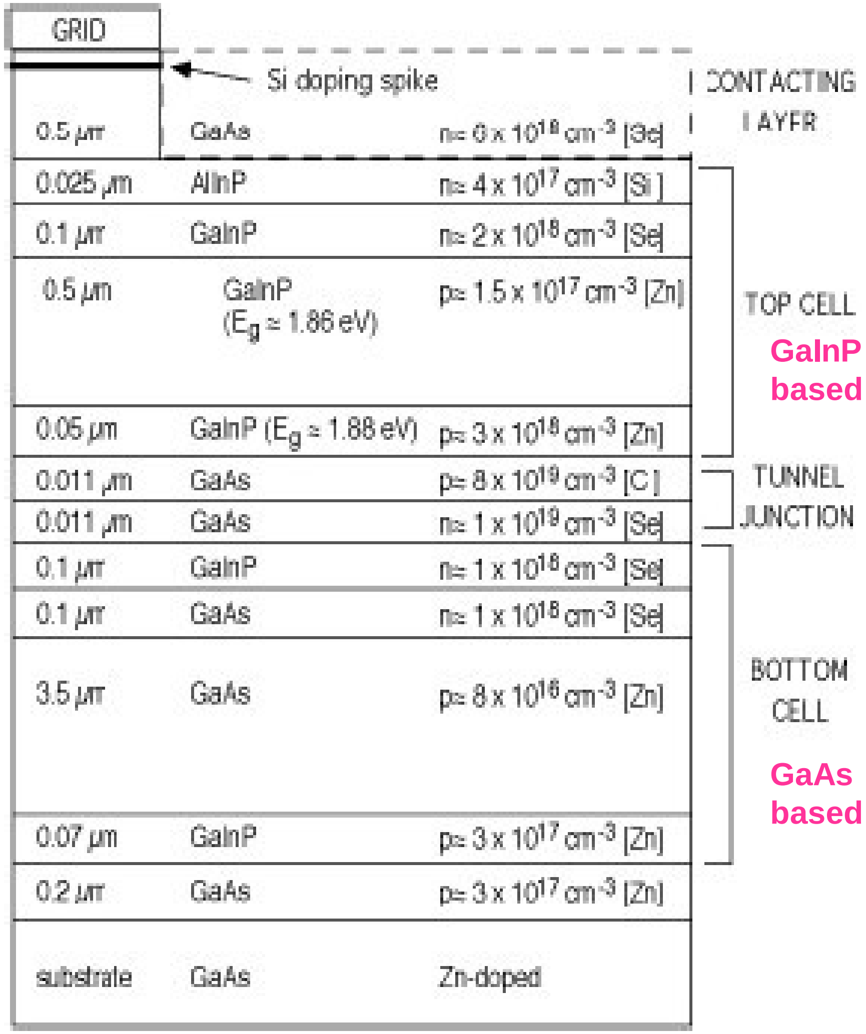


$E_{g1} > E_{g2} > E_{g3}$

Semiconductor combinations for multi-junction solar cells



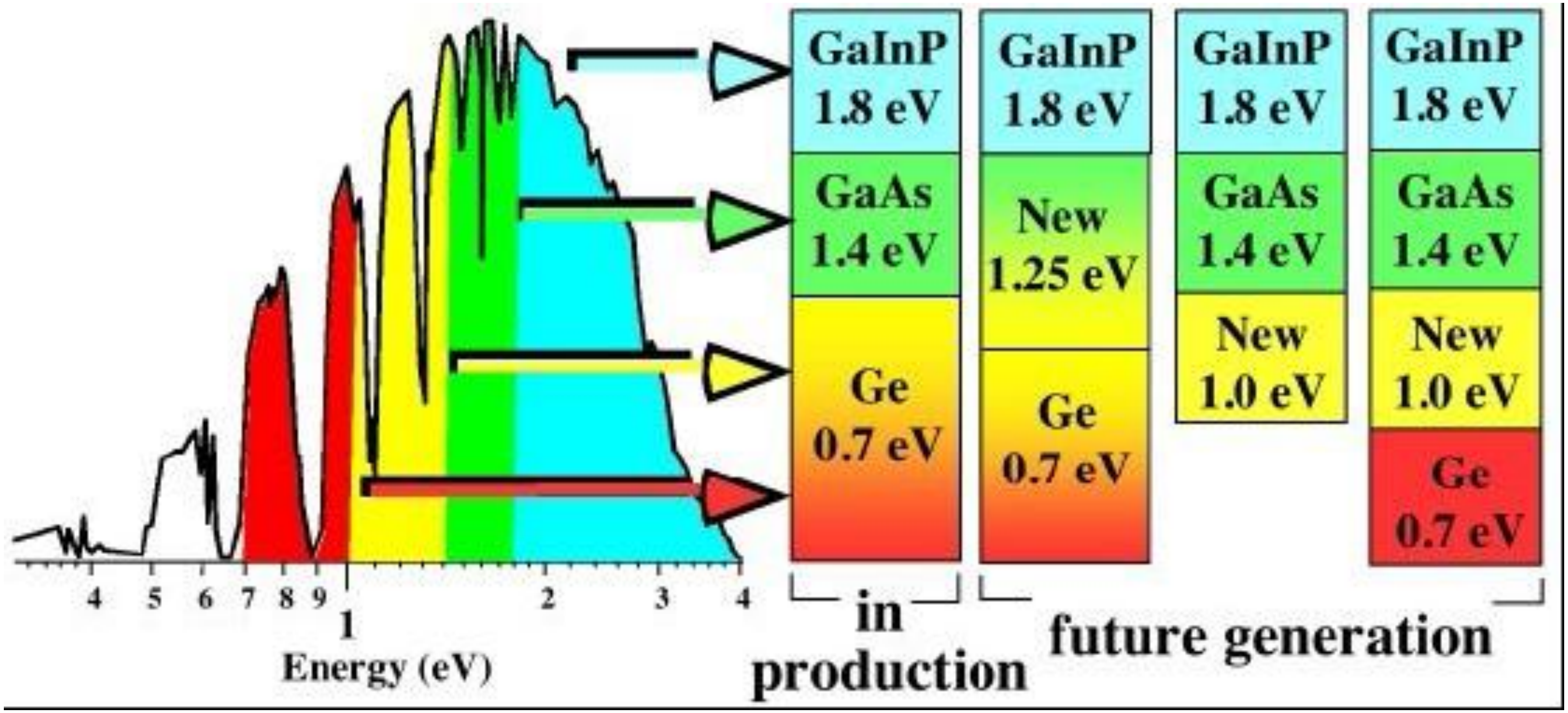
4 terminals to 2 terminals



GRID

Si doping spike

0.5 µm	GaAs	$n \approx 6 \times 10^{18}\ cm^{-3}$ [Se]	CONTACTING LAYER
0.025 µm	AlInP	$n \approx 4 \times 10^{17}\ cm^{-3}$ [Si]	TOP CELL **GaInP based**
0.1 µm	GaInP	$n \approx 2 \times 10^{18}\ cm^{-3}$ [Se]	
0.5 µm	GaInP ($E_g \approx 1.86$ eV)	$p \approx 1.5 \times 10^{17}\ cm^{-3}$ [Zn]	
0.05 µm	GaInP ($E_g \approx 1.88$ eV)	$p \approx 3 \times 10^{18}\ cm^{-3}$ [Zn]	
0.011 µm	GaAs	$p \approx 8 \times 10^{19}\ cm^{-3}$ [C]	TUNNEL JUNCTION
0.011 µm	GaAs	$n \approx 1 \times 10^{19}\ cm^{-3}$ [Se]	
0.1 µm	GaInP	$n \approx 1 \times 10^{18}\ cm^{-3}$ [Se]	BOTTOM CELL **GaAs based**
0.1 µm	GaAs	$n \approx 1 \times 10^{18}\ cm^{-3}$ [Se]	
3.5 µm	GaAs	$p \approx 8 \times 10^{16}\ cm^{-3}$ [Zn]	
0.07 µm	GaInP	$p \approx 3 \times 10^{17}\ cm^{-3}$ [Zn]	
0.2 µm	GaAs	$p \approx 3 \times 10^{17}\ cm^{-3}$ [Zn]	
substrate	GaAs	Zn-doped	

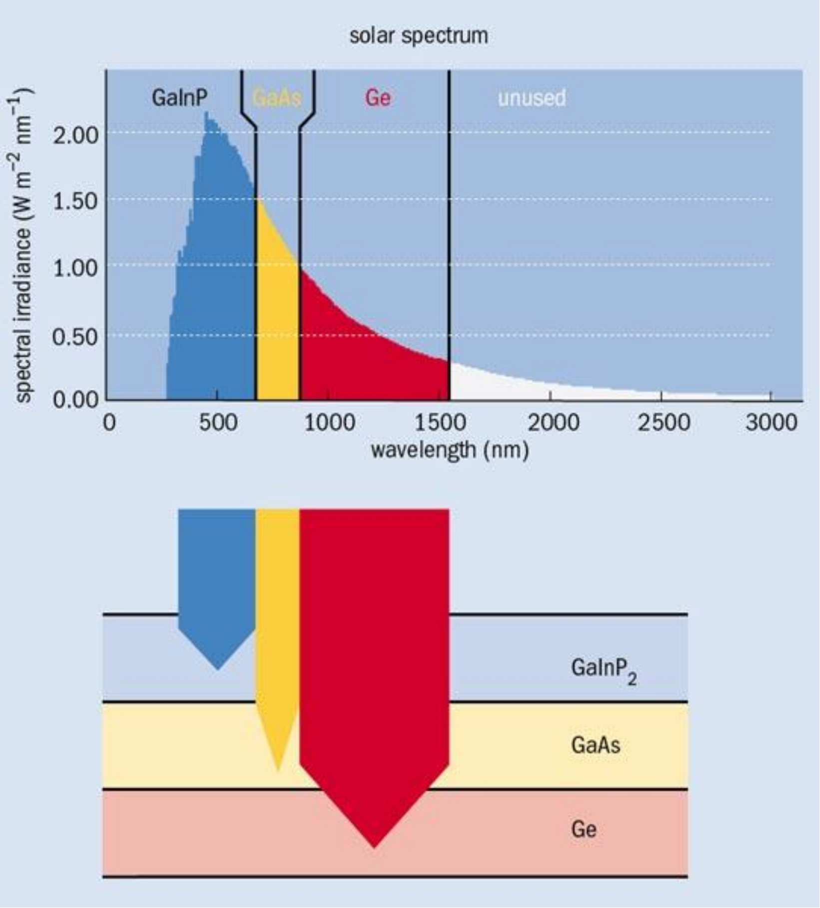


Several combinations:

GaAs/InGaP and Ge/InGaAsN

InP/InAlAs and InP/InGaAs

GaN/InGaN to cover almost the whole range



The solar spectrum AM0 peaks at 500 nm but extends to beyond 3 µm. The unconcentrated triple-junction solar cell GaInP/GaAs/Ge, which has bandgaps of 1.88, 1.42 and 0.67 eV, respectively, can absorb a high proportion of this radiation and deliver an efficiency of almost 30%.

Ref: http://compoundsemiconductor.net/cws/article/magazine/31311

LIGHT EMITTING DIODES

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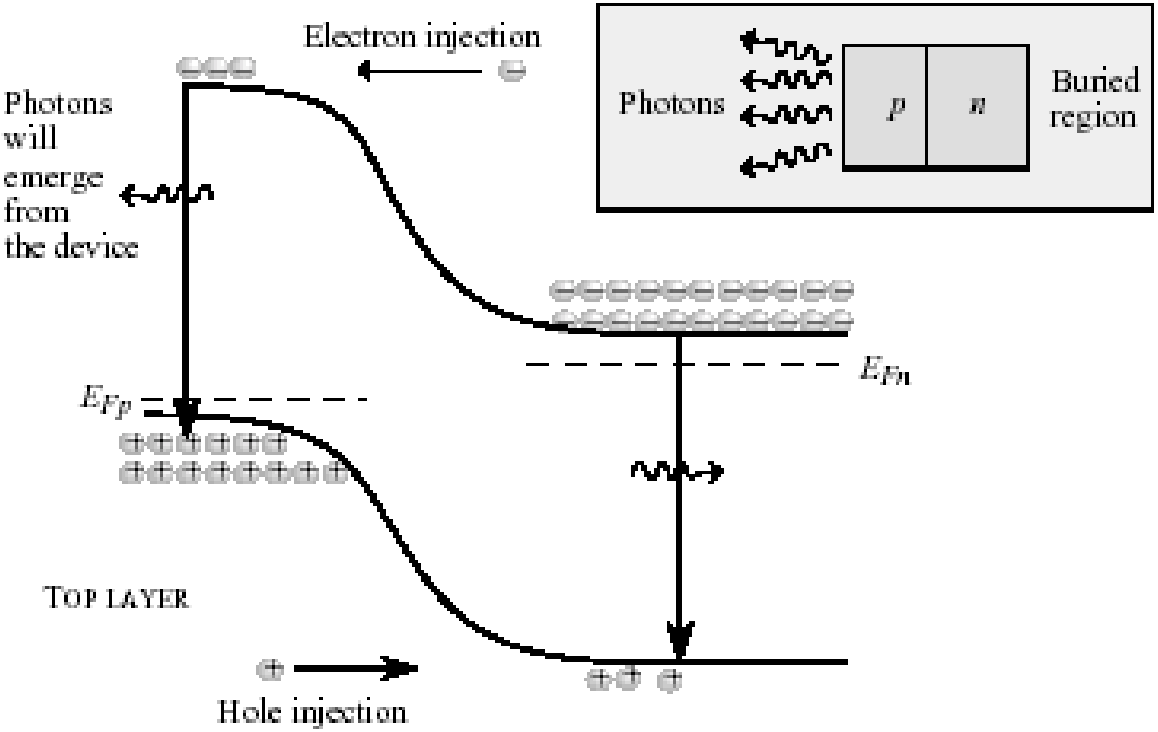
LIGHT EMITTING DIODES

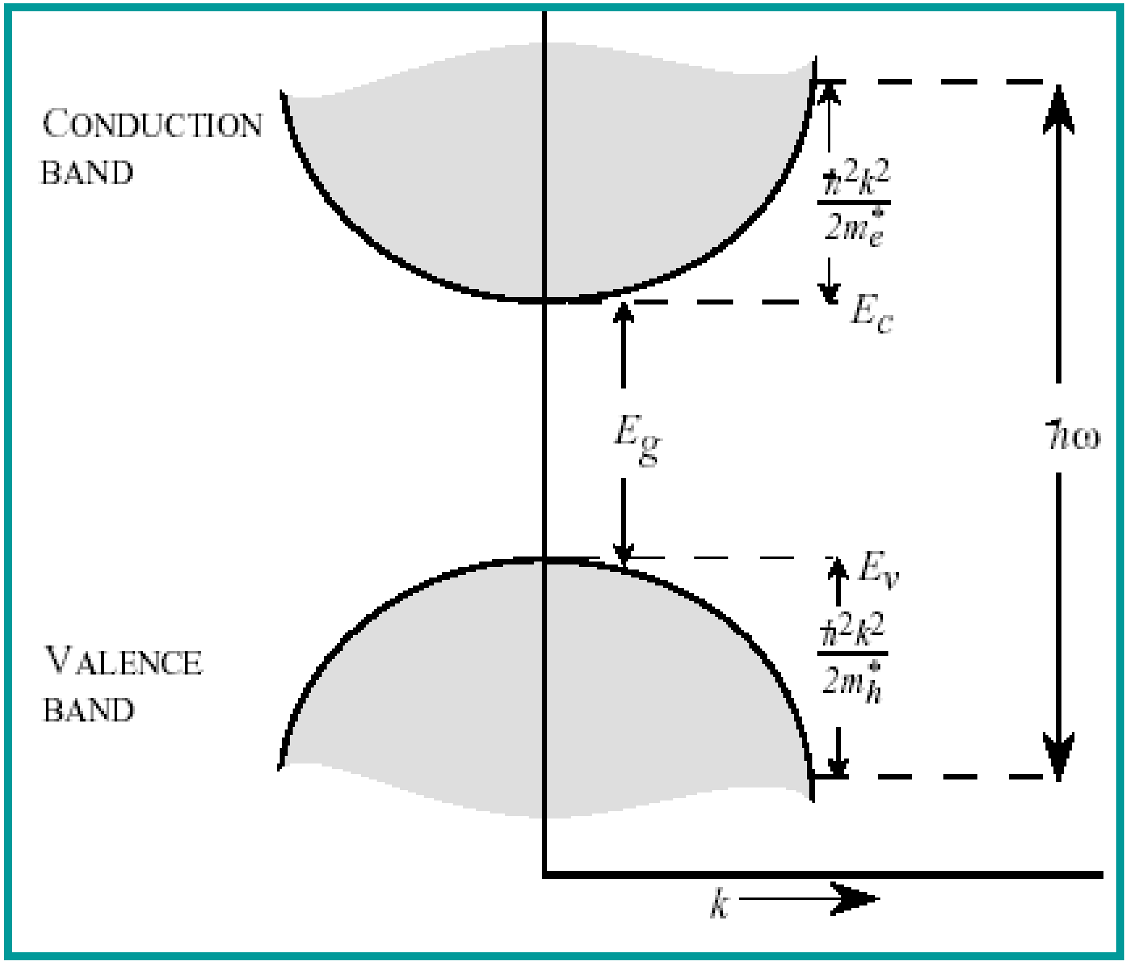


Emitted photon energy ~E_g
Emitted spectral linewidth ~k_BT
Upper limit to LED switching time ~1 ns ← electron-hole recombination time

Source: Singh

LIGHT EMITTING DIODES

ELECTRON-HOLE RECOMBINATION TIMES



- Electrons and holes recombine in LEDs via a process called *spontaneous recombination*.
- Energy-momentum conservation rules apply.

Recombination rate $\alpha f^e(k) \cdot f^h(k)$

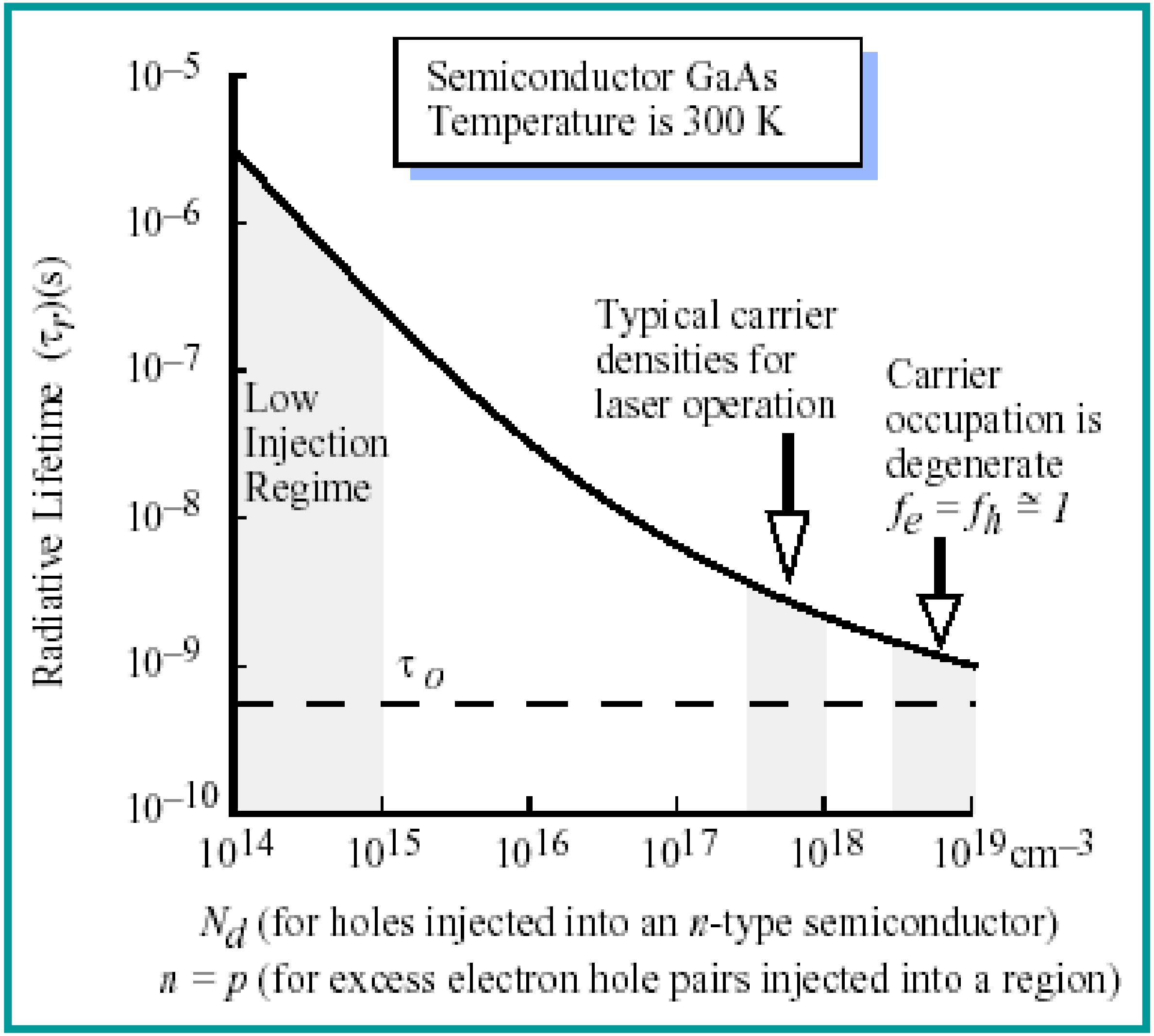
$f^e(k)$: probability of finding an electron with momentum $\hbar k$

$f^h(k)$: probability of finding a hole with momentum $\hbar k$

Source: Singh

RADIATIVE RECOMBINATION

ELECTRON-HOLE RECOMBINATION TIMES



- e-h recombination time proportional to carrier density

- At high carrier density $\tau_0 \sim 1$ ns

Source: Singh

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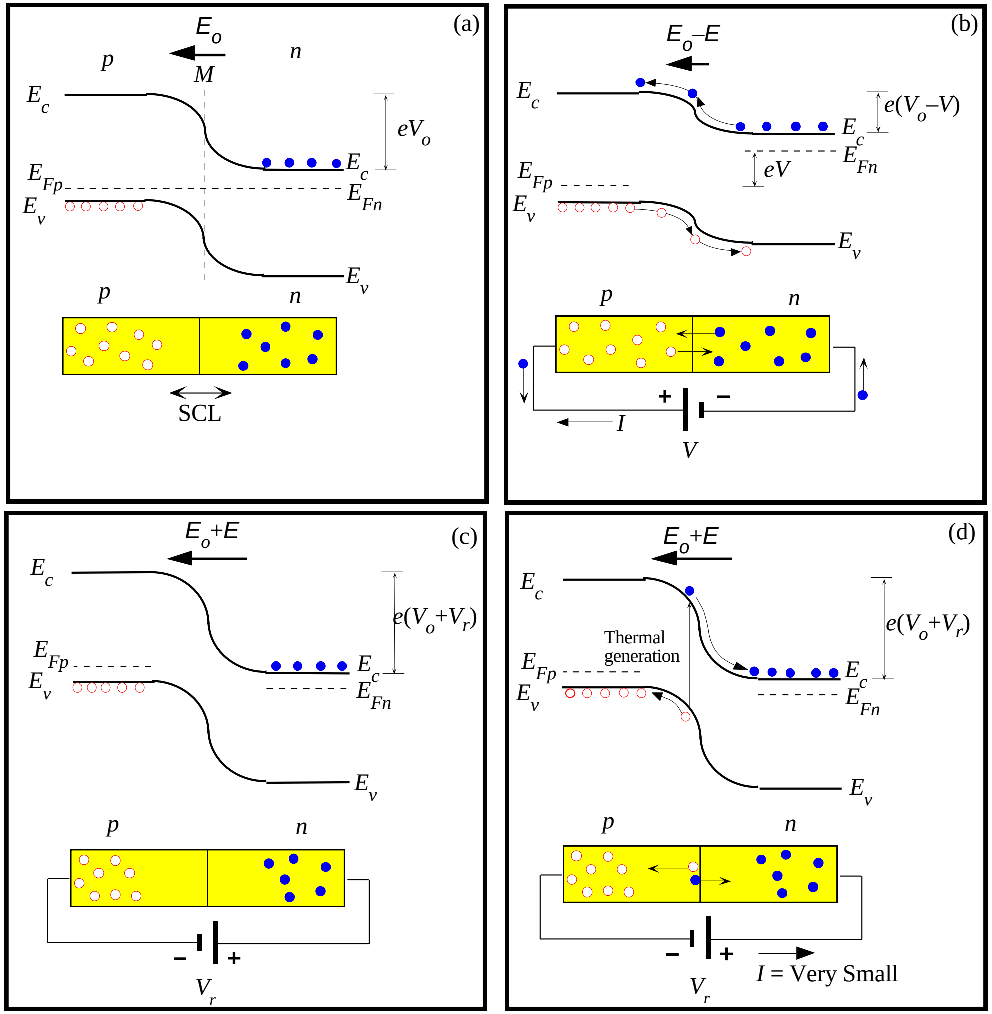
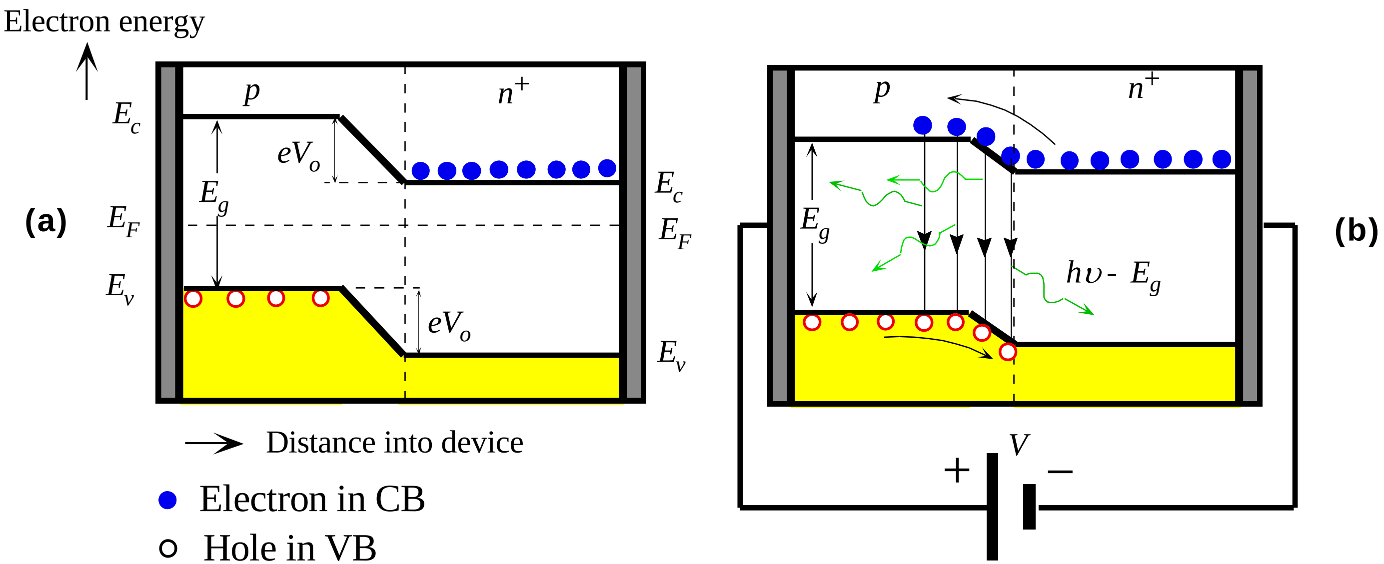
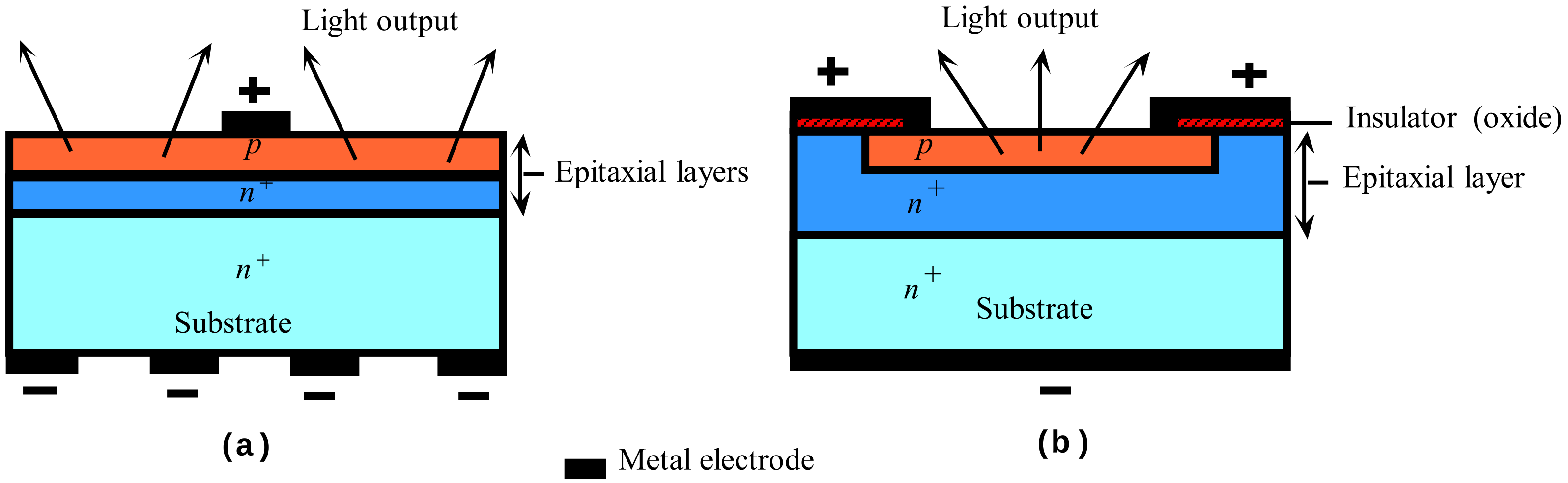


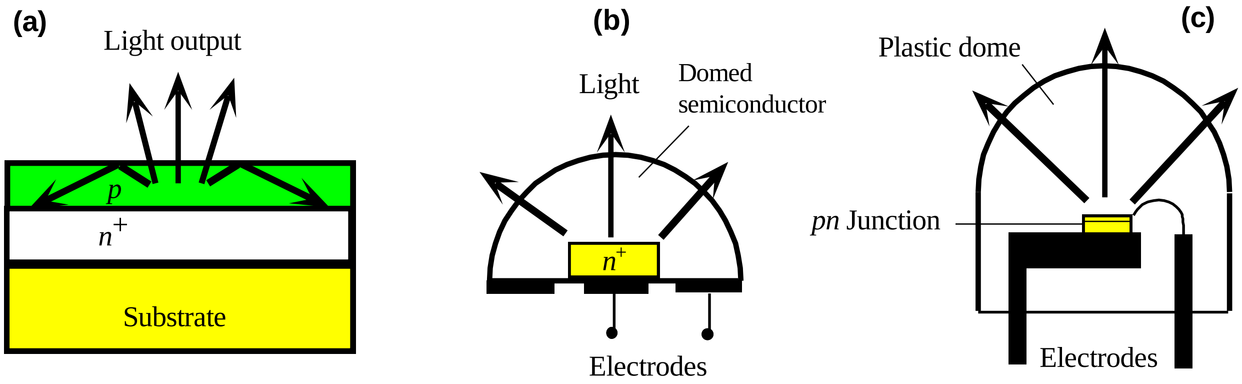
Energy band diagrams for a *pn* junction under (a) open circuit, (b) forward bias and (c) reverse bias conditions. (d) Thermal generation of electron hole pairs in the depletion region results in a small reverse current.



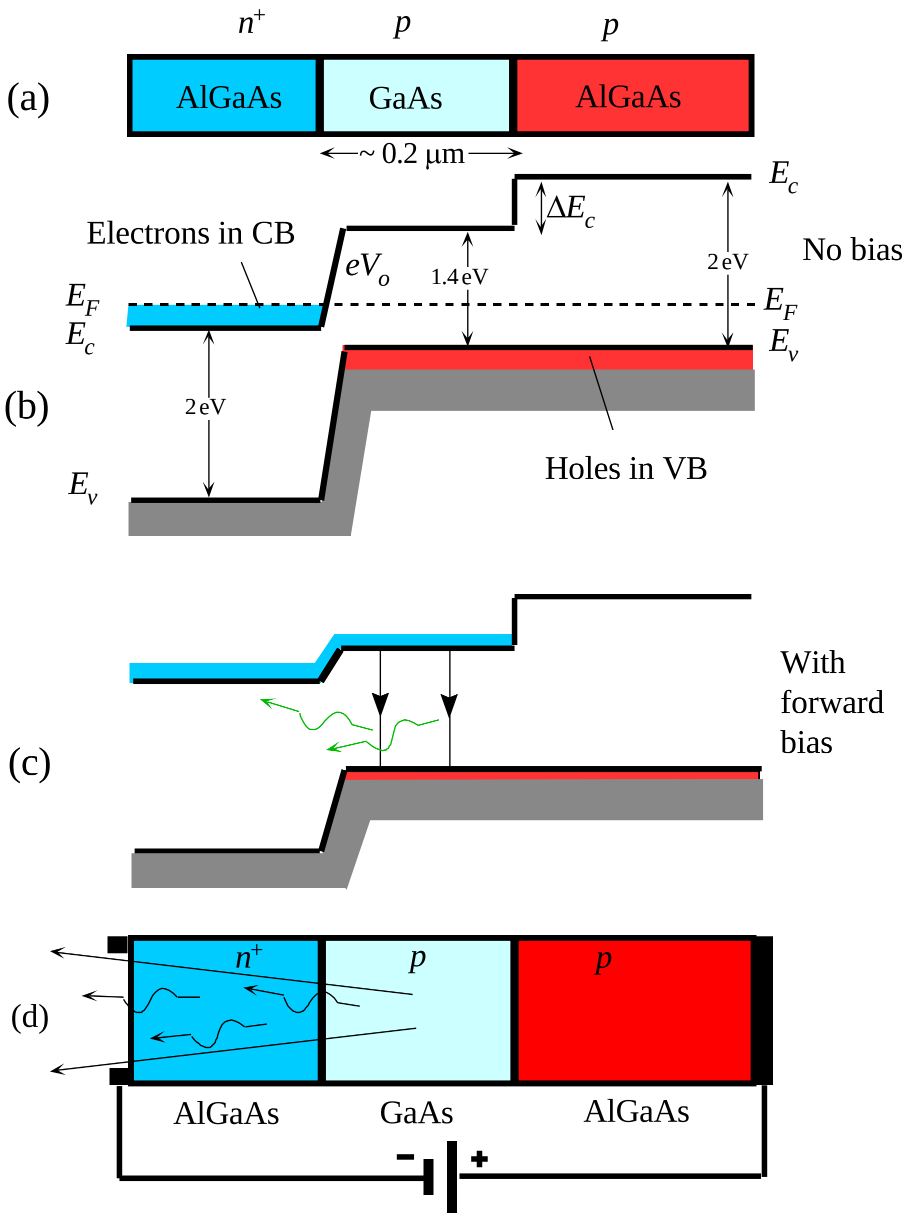
(a) The energy band diagram of a p-n^+ (heavily n-type doped) junction without any bias. Built-in potential V_o prevents electrons from diffusing from n^+ to p side. (b) The applied bias reduces V_o and thereby allows electrons to diffuse, be injected, into the p-side. Recombination around the junction and within the diffusion length of the electrons in the p-side leads to photon emission.



A schematic illustration of typical planar surface emitting LED devices. (a) p-layer grown epixially on an n^+ Substrate (b) First n^+ is epitaxially grown and then p-region is formed by dopant diffusion into the epitaxial layer



(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 dome so that the angles of incidence at the semiconductor-air surface are smaller than th critical angle. (b) An economic method of allowing more light to escape from the LED is to encapsulate it in a transparent plastic dome.



(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.

(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.

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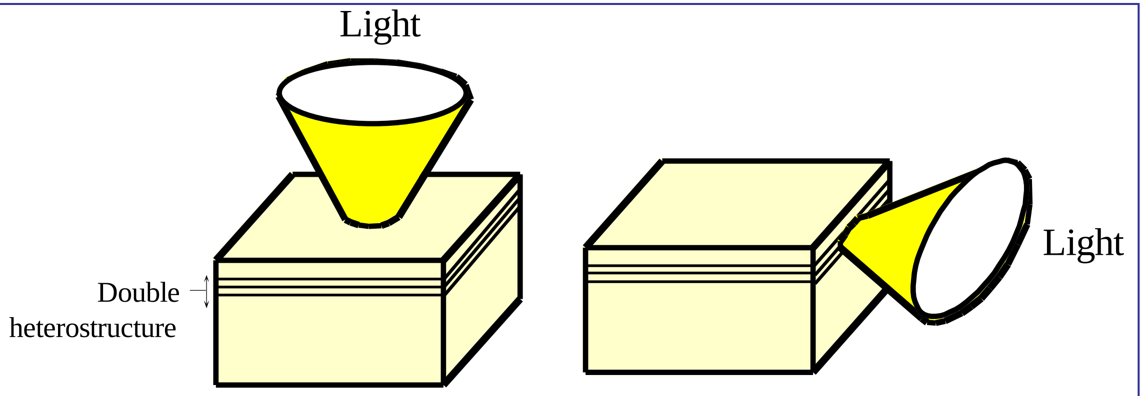
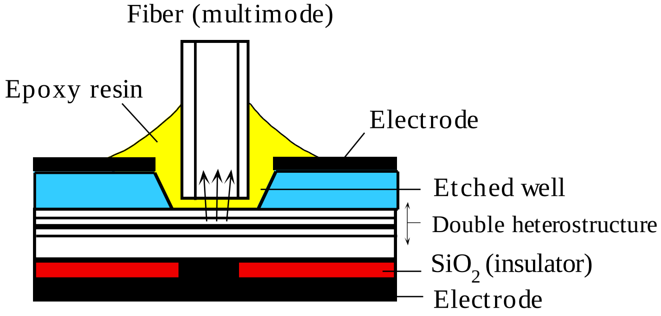
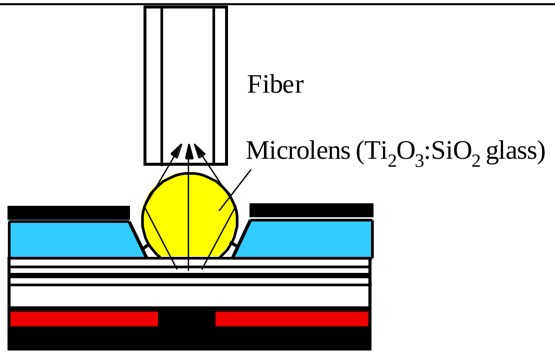


(a) Surface emitting LED (b) Edge emitting LED



(a)

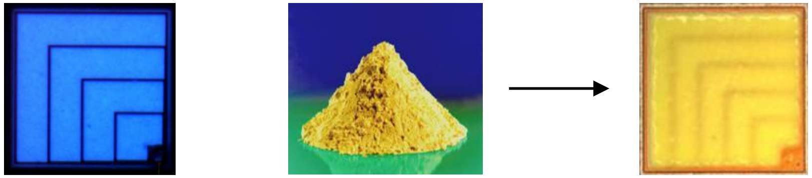
Light is coupled from a surface emitting LED into a multimode fiber using an index matching epoxy. The fiber is bonded to the LED structure.



(b)

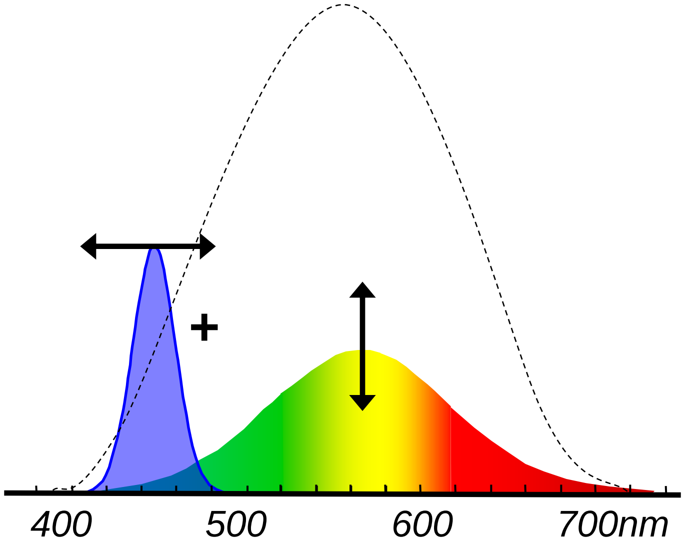
A microlens focuses diverging light from a surface emitting LED into a multimode optical fiber.

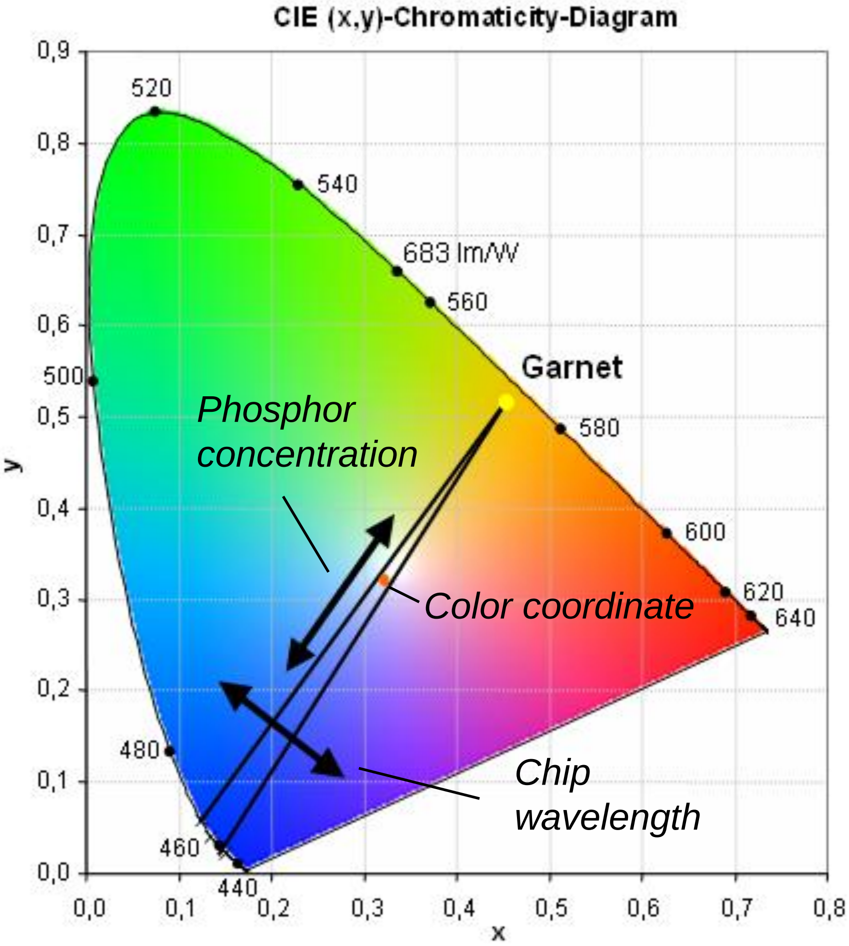
White Light by Phosphor Conversion



Blue LED

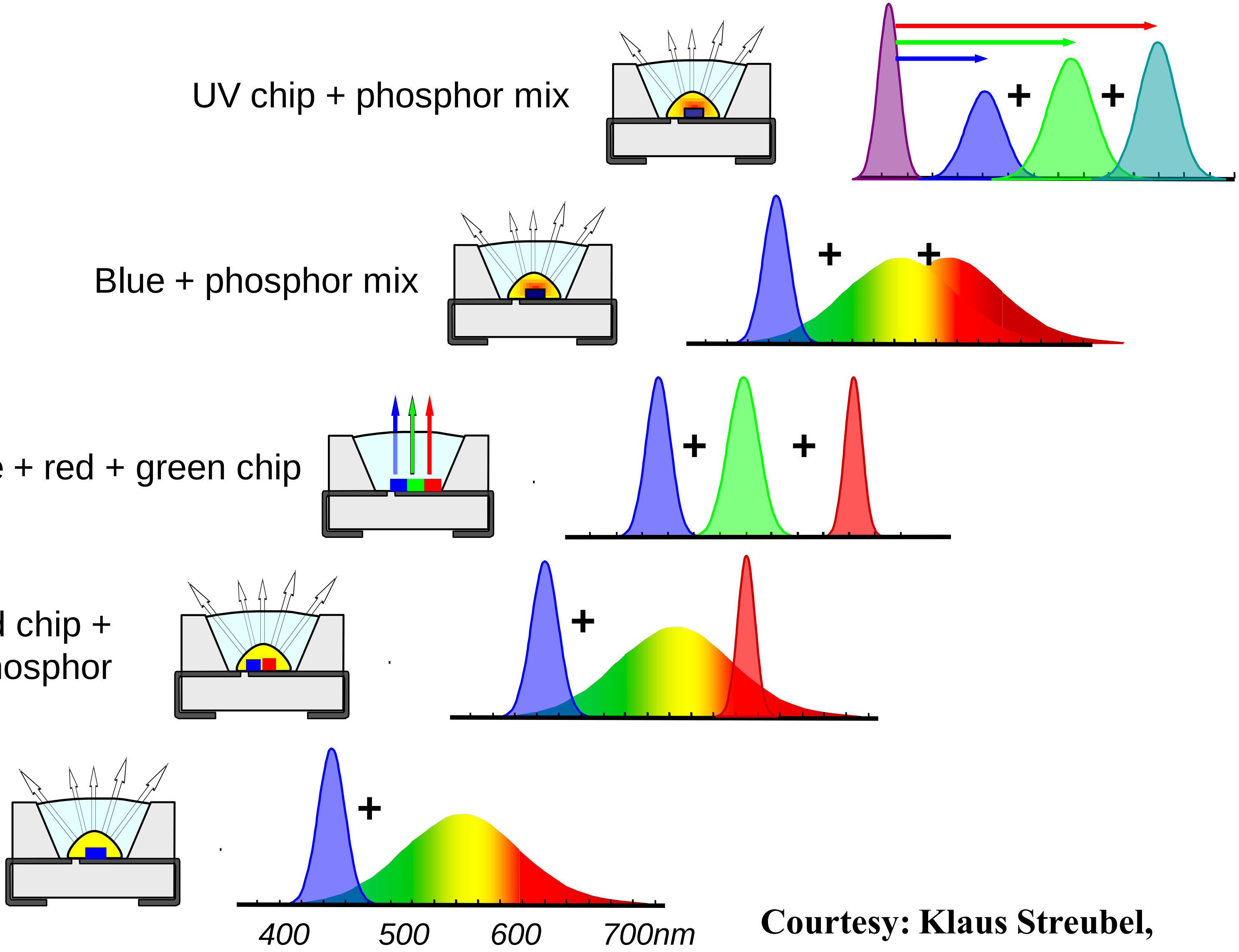
Yellow phosphor





Courtesy: Klaus Streubel, Osram

White LEDs



UV chip + phosphor mix

Blue + phosphor mix

Blue + red + green chip

Blue + red chip +
Yellow phosphor

Blue chip +
Yellow
phosphor

Courtesy: Klaus Streubel, Osram

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LASERS

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CONDITIONS FOR STIMULATED EMISSION

- **Under thermal eqm. and for $(E_2-E_1) > 3kT$:**

$n_2/n_1 = \exp -[(E_2-E_1)/kT] = \exp -(hv/kT)$

i.e., at thermal eqm., low lying levels are more populated ($n_1>n_2$)

- **Under steady state conditions:**

Stimulated emission rate + Spontaneous emission rate = Absorption rate

$$B_{21}n_2\rho(hv_{12}) \quad + \quad A_{21}n_2 \quad = \quad B_{12}n_1\,\rho(hv_{12})$$

A’s and B’s are constants

$\rho(hv_{12})$ = photon field energy density, i.e., the total energy in the radiation field per unit volume per unit frequecy

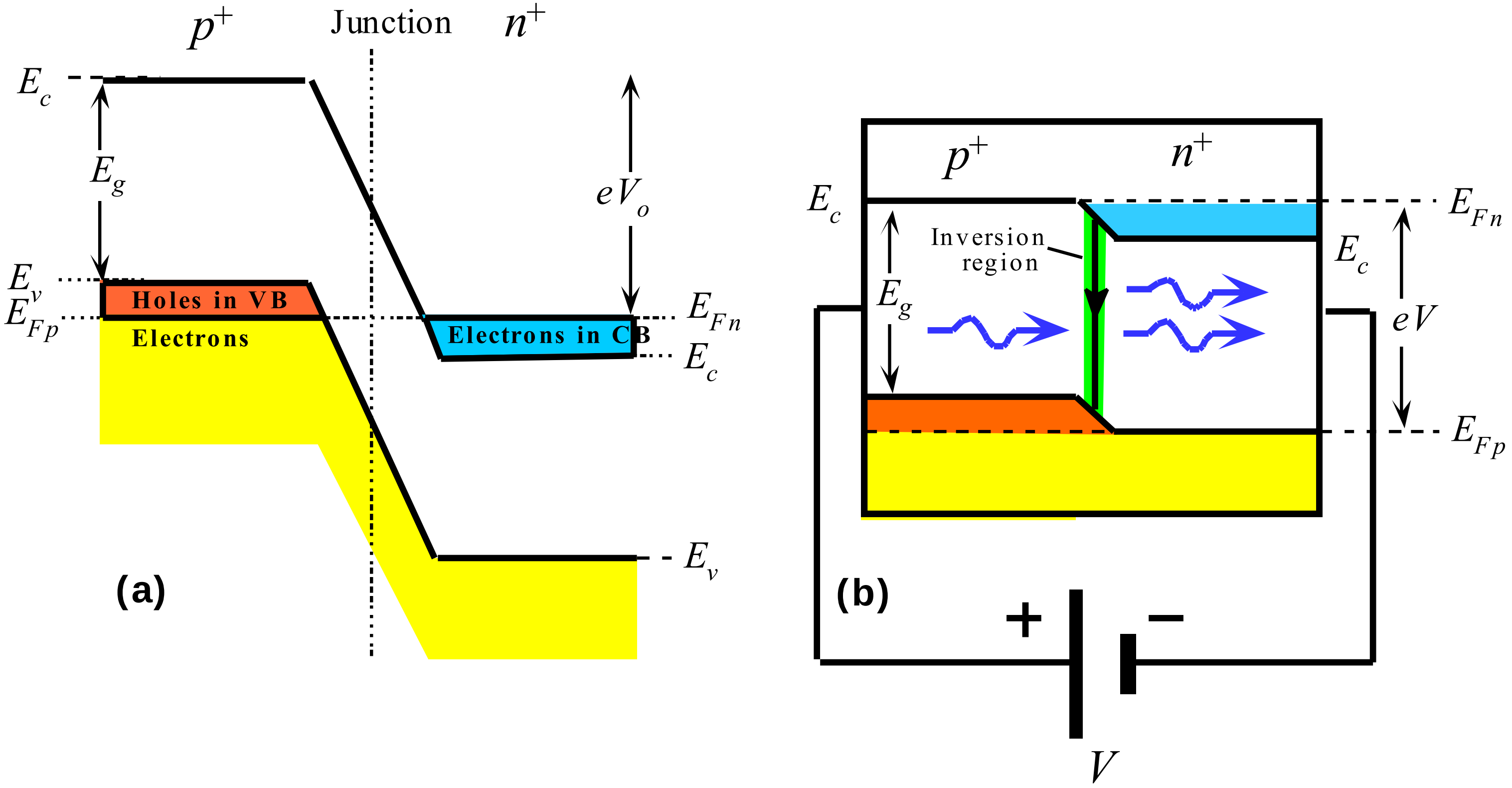
Stimulated emission rate/Spontaneous emission rate = $(B_{21}/A_{21})\,\rho(hv_{12})$

$\Rightarrow$ To enhance stimulated emission, large $\rho(hv_{12})$ is necessary

Stimulated emission rate / Absorption rate = $(B_{21}/B_{12})\,(n_2/n_1)$

$\Rightarrow$ To enhance stimuated emission, $n_2>n_1$ i.e., population inversion necessary

POPULATION INVERSION AND STIMULATED EMISSION



The energy band diagram of a degenerately doped *p-n* with no bias. (b) Band diagram with a sufficiently large forward bias to cause population inversion and hence stimulated emission.

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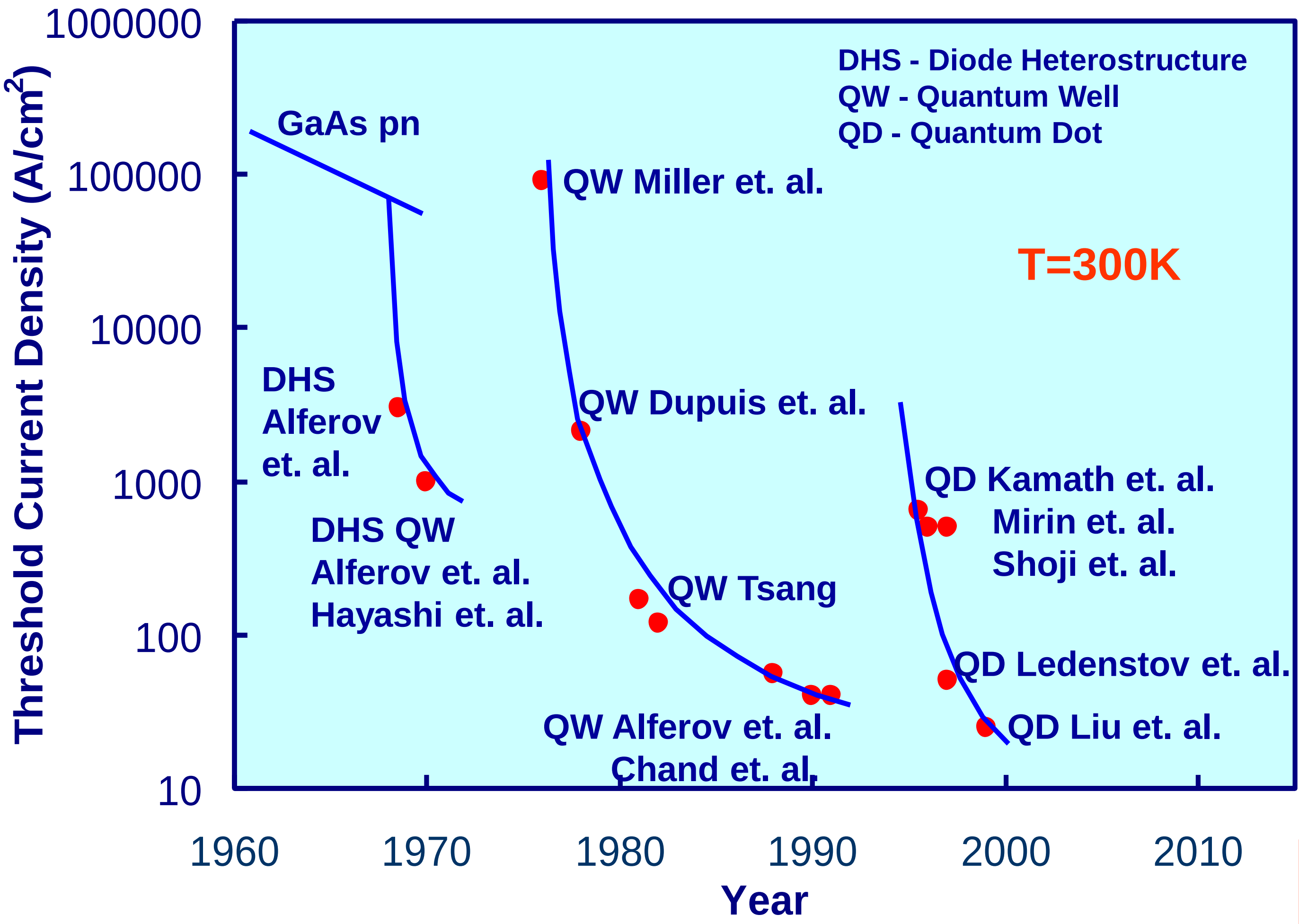
History of Heterostructure Lasers



Courtesy:
P.Bhattacharya,
University of
Michigan

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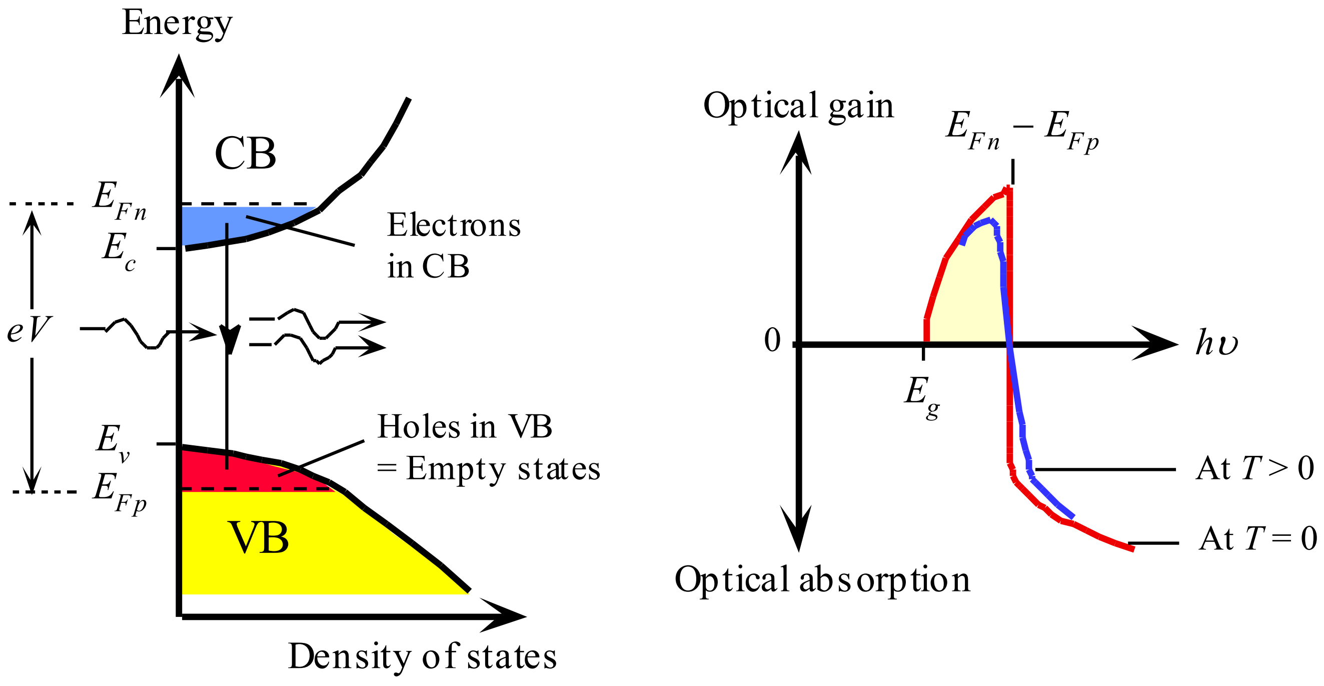
POPULATION INVERSION AND STIMULATED EMISSION



(a) **(b)**

(a) The density of states and energy distribution of electrons and holes in the conduction and valence bands respectively at $T \approx 0$ in the SCL under forward bias such that $E_{Fn} - E_{Fp} > E_g$. Holes in the VB are empty states. (b) Gain vs. photon energy.

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SCL =space charge layer
= depletion layer

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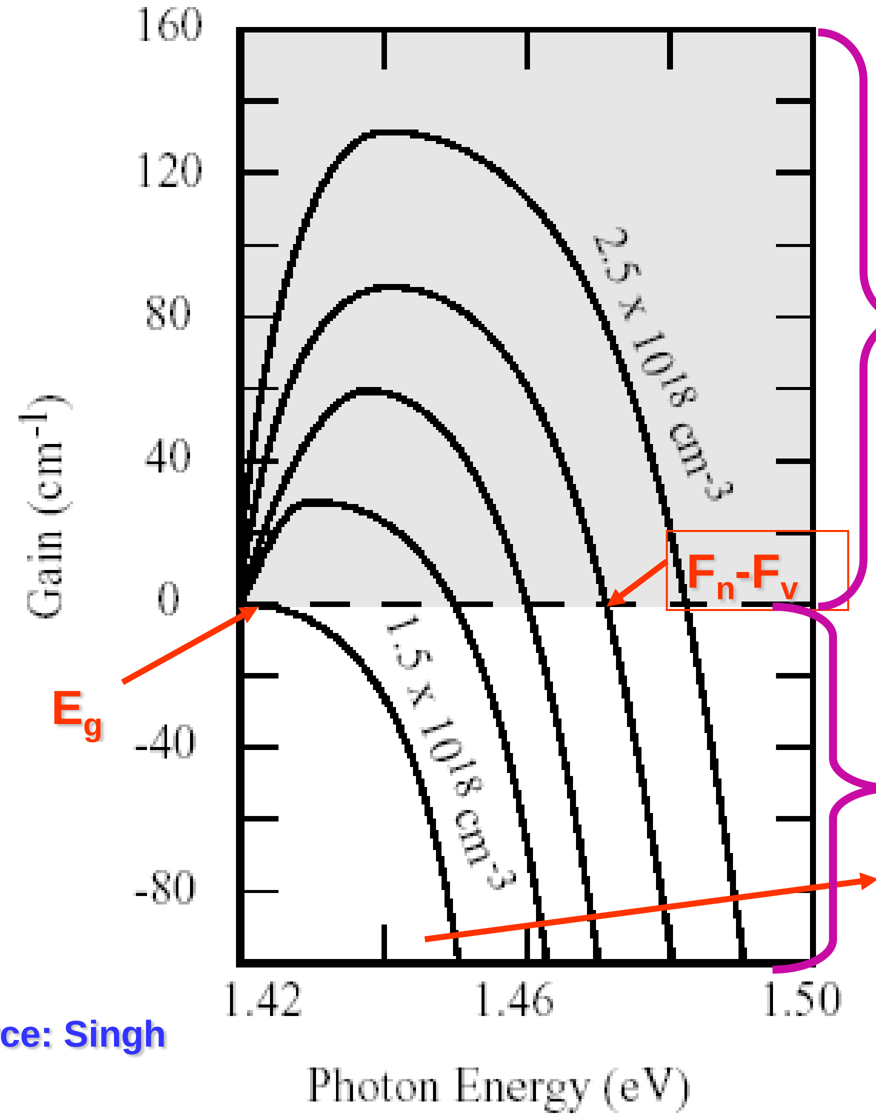
Gain or loss? When?

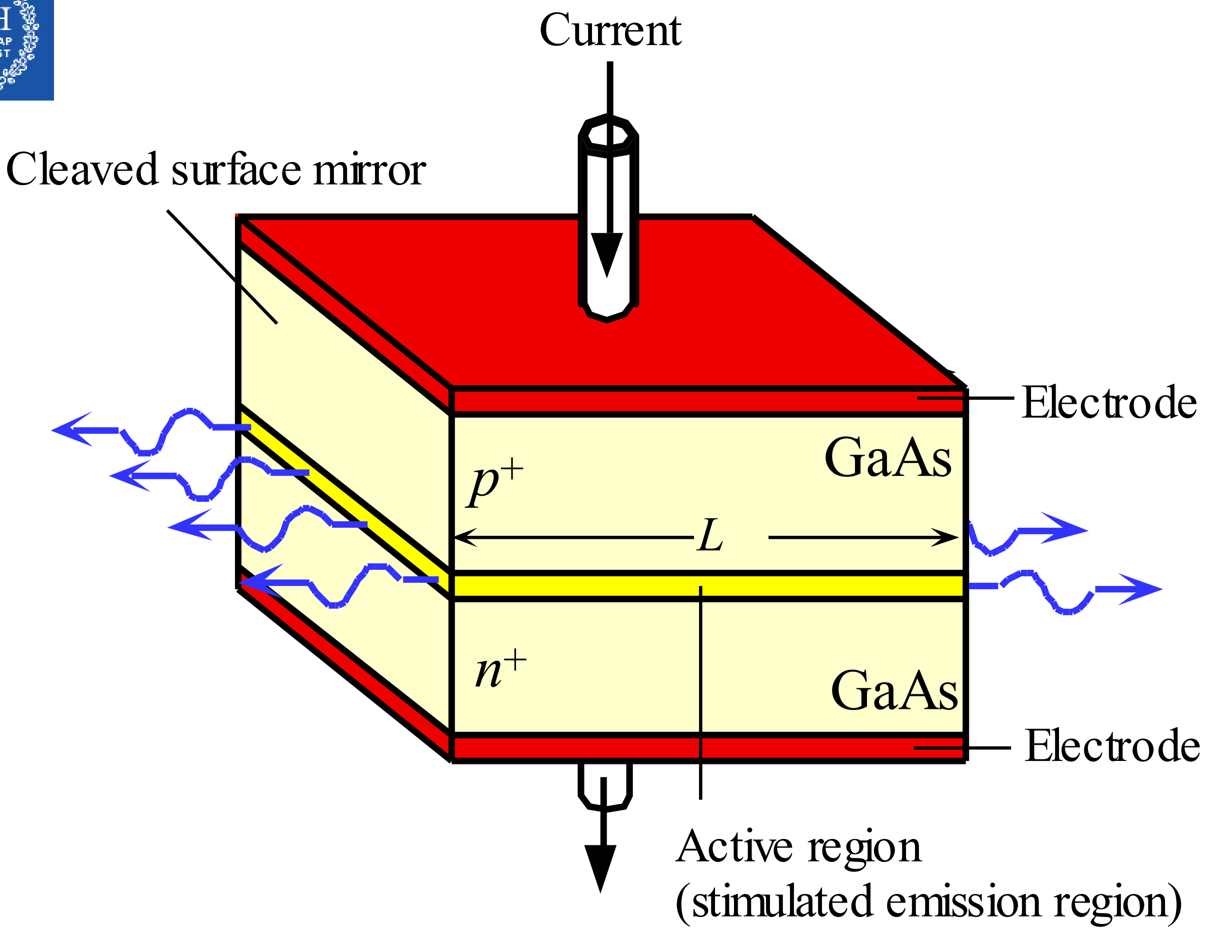


Source: Singh

- Photon with energy < E_g cannot excite an electron and hence are transparent => No gain!
- Photon with energy between E_g and F_n-F_v can stimulate recombination => Hence gain!
- Photon with energy > F_n-F_v will only be absorbed! => No gain - only loss!

Increasing carrier density

To get good lasers:
Optimise
Confinement
Cavity gain
Cavity loss
Mirror loss



A schematic illustration of a GaAs homojunction laser diode. The cleaved surfaces act as reflecting mirrors.

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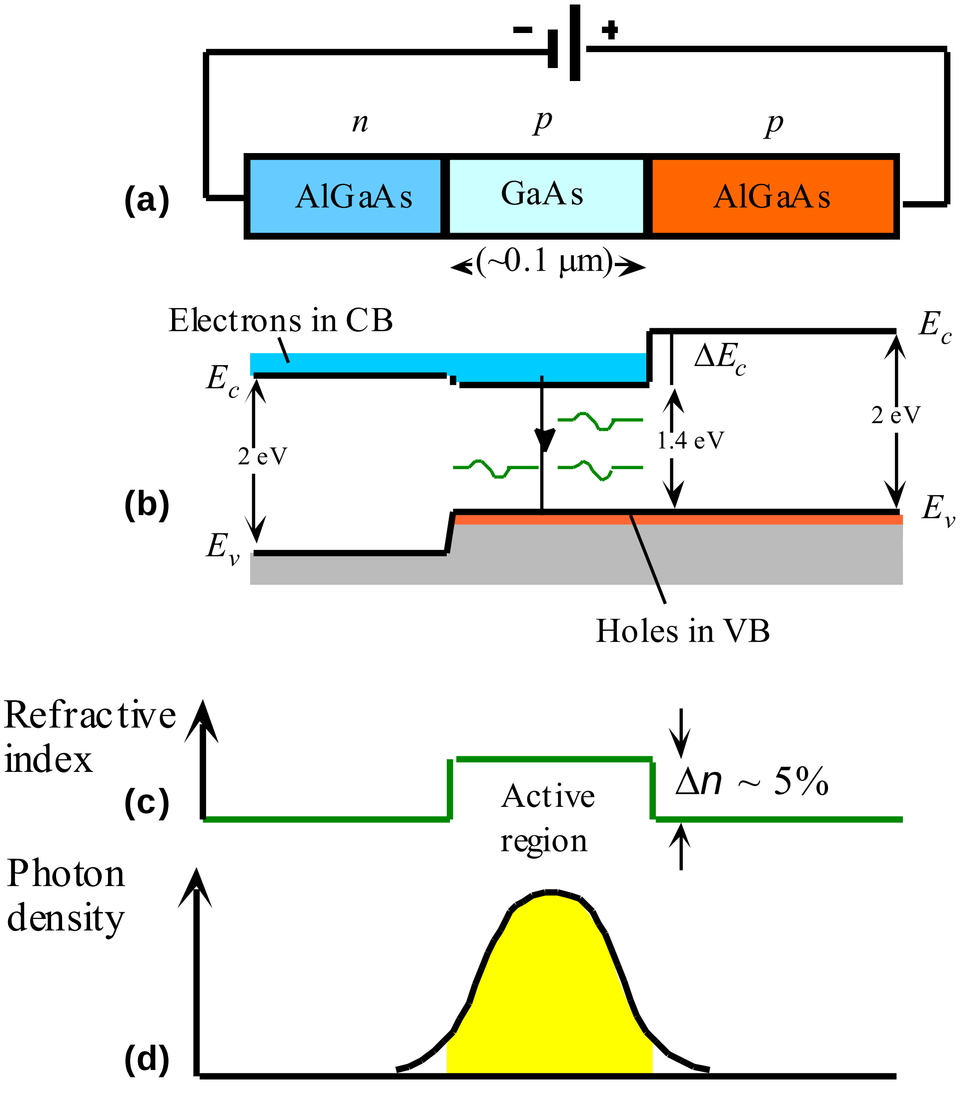
Optical cavity, produced by cleaving the crystal causes photons to be reflected back into the cavity. The photon build-up starts the stimulated emission responsible for lasing

No optical confinement and no carrier confinement in homojunctions!



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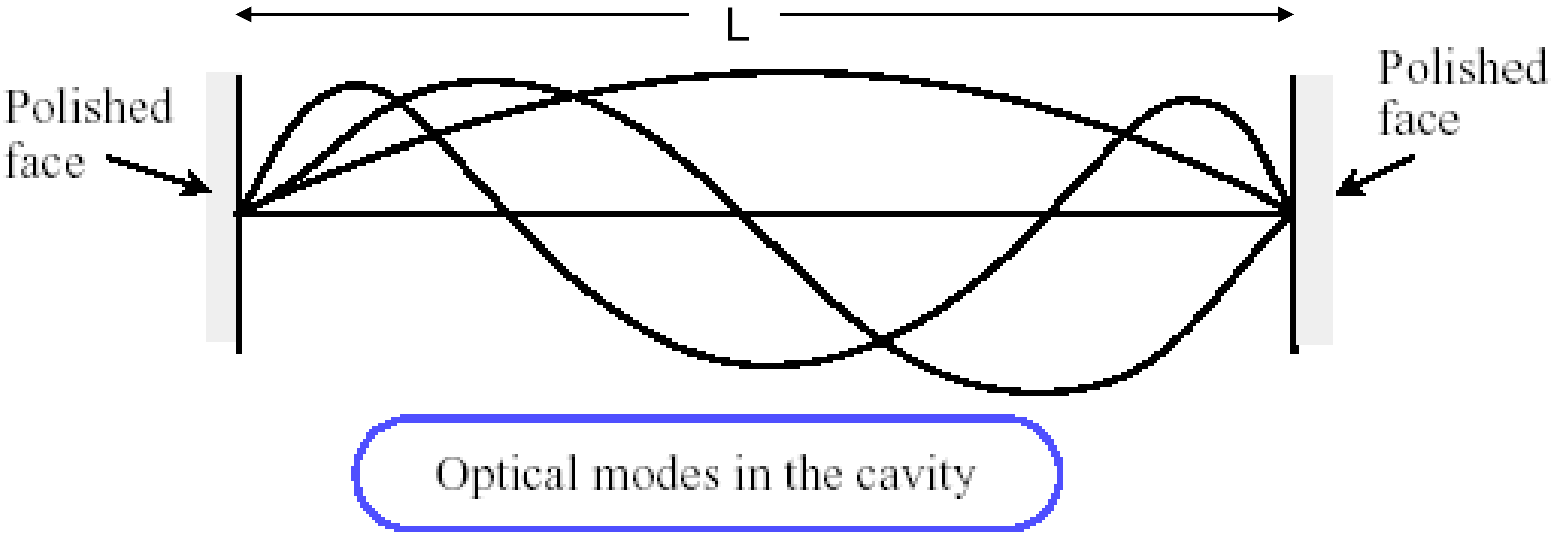
(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs).

(b) Simplified energy band diagram under a large forward bias. Lasing recombination takes place in the *p*-GaAs layer, the *active layer*

(c) Higher bandgap materials have a lower refractive index

(d) AlGaAs layers provide lateral optical confinement.

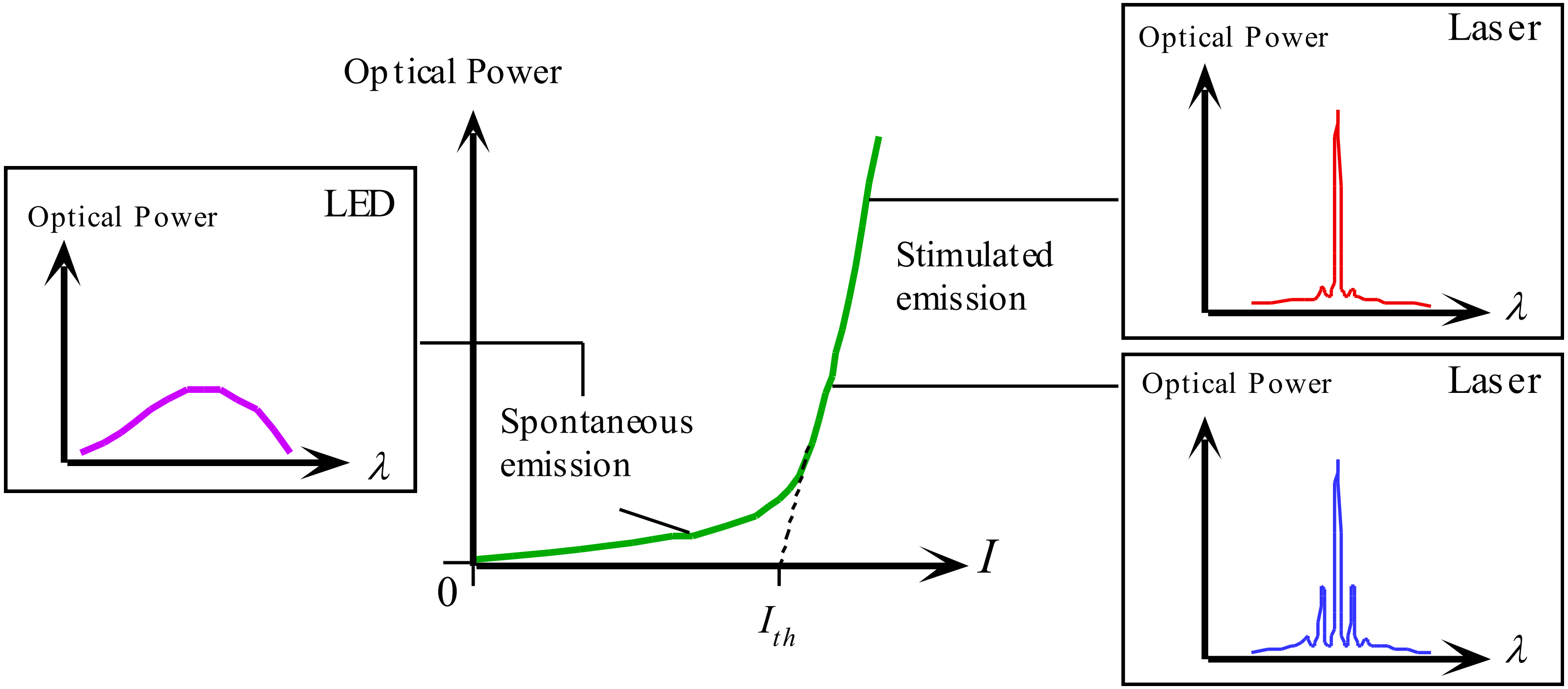


The resonant modes supported by the cavity are those that satisfy

$L = m\,\lambda/2$

m = integer; λ = light wavelength in the material = λ_0/ref.index

Source: Singh



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

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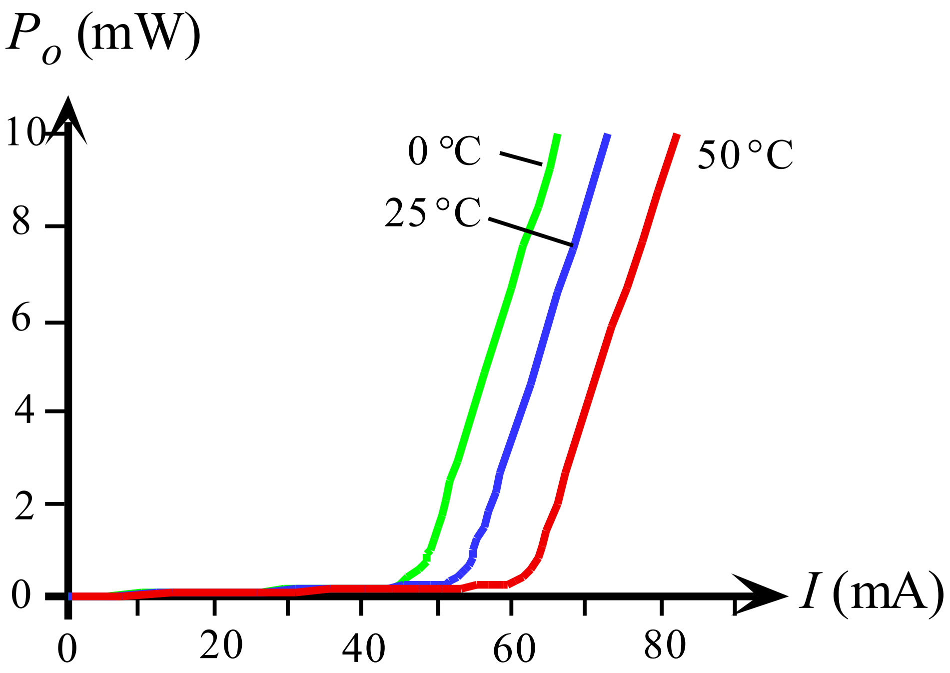
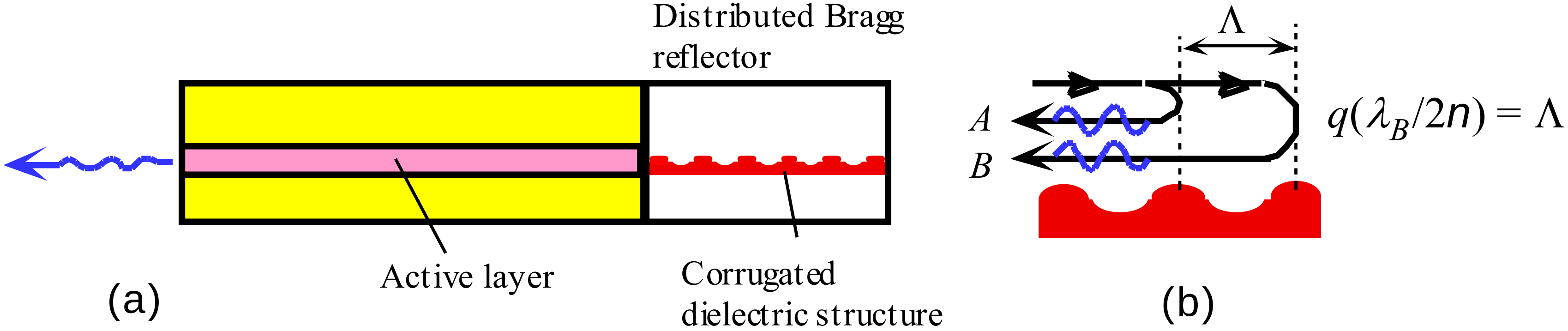


Output optical power vs. diode current as three different temperatures. The threshold current shifts to higher temperatures.

SINGLE FREQUENCY LASERS:

DISTRIBUTED FEED BACK (DFB) LASERS AND DISTRIBUTED BRAGG REFLECTOR (DBR) LASERS



(a) Distributed Bragg reflection (DBR) laser principle. (b) Partially reflected waves at the corrugations can only constitute a reflected wave when the wavelength satisfies the Bragg condition. Reflected waves *A* and *B* interfere constructive when $q(\lambda_B/2n) = \Lambda$.

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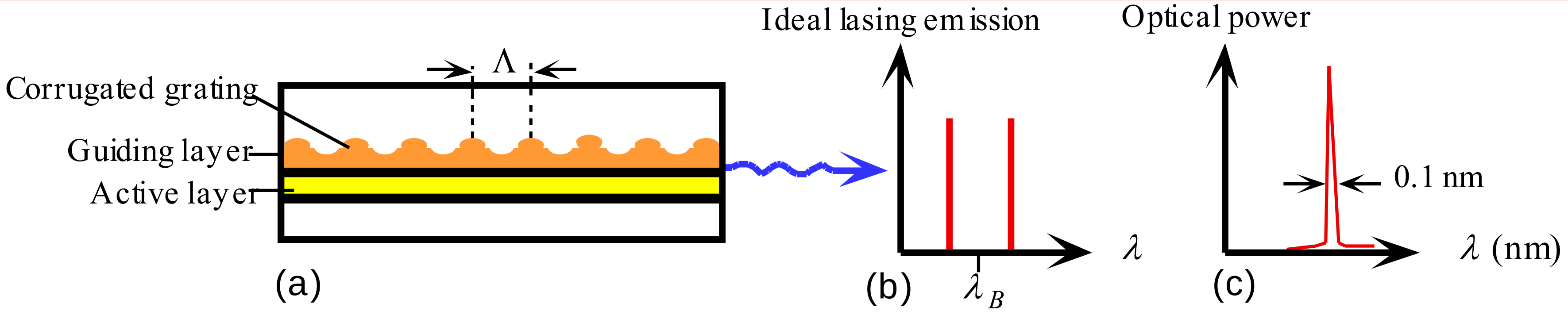
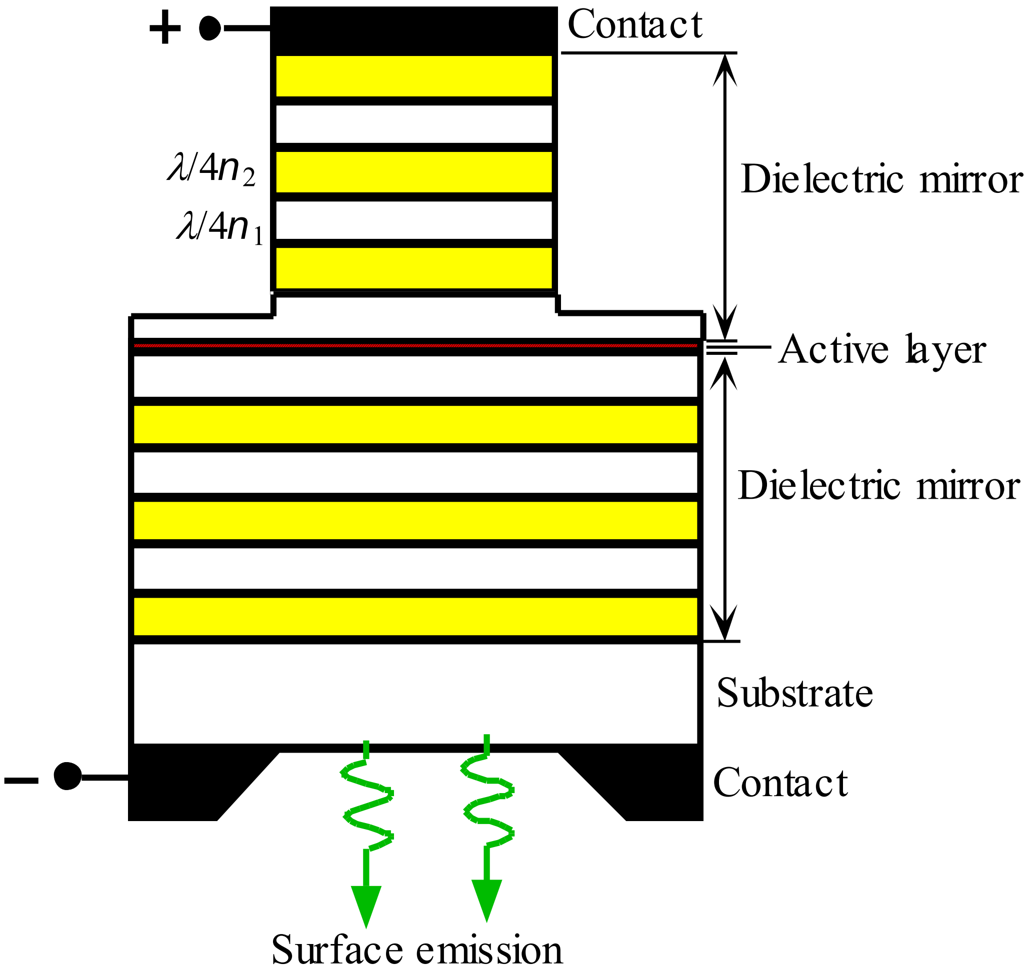
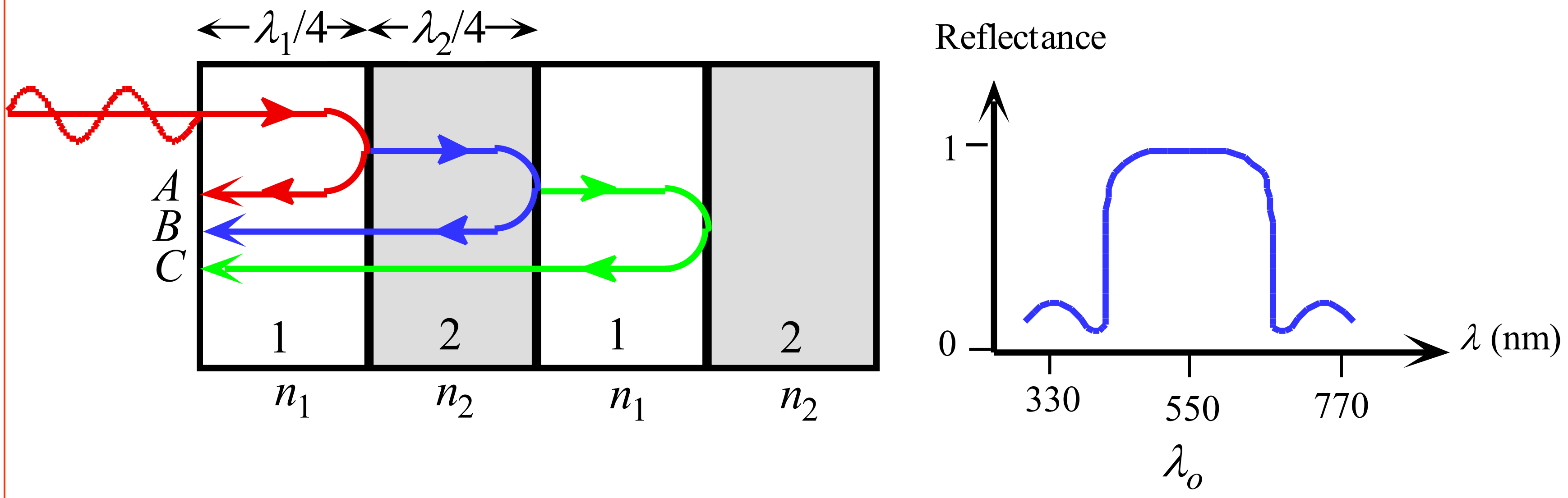
q = integer
n = ref. index
Λ = period of the gratings



(a) Distributed feedback (DFB) laser structure. (b) Ideal lasing emission output. (c) Typical output spectrum from a DFB laser.

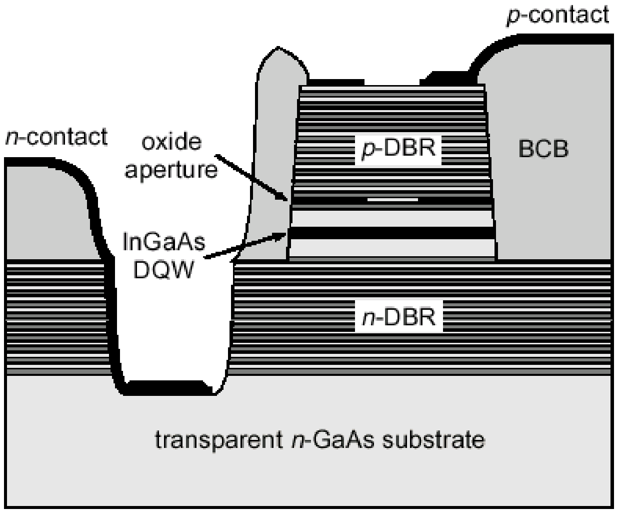


A simplified schematic illustration of a vertical cavity surface emitting laser (VCSEL).



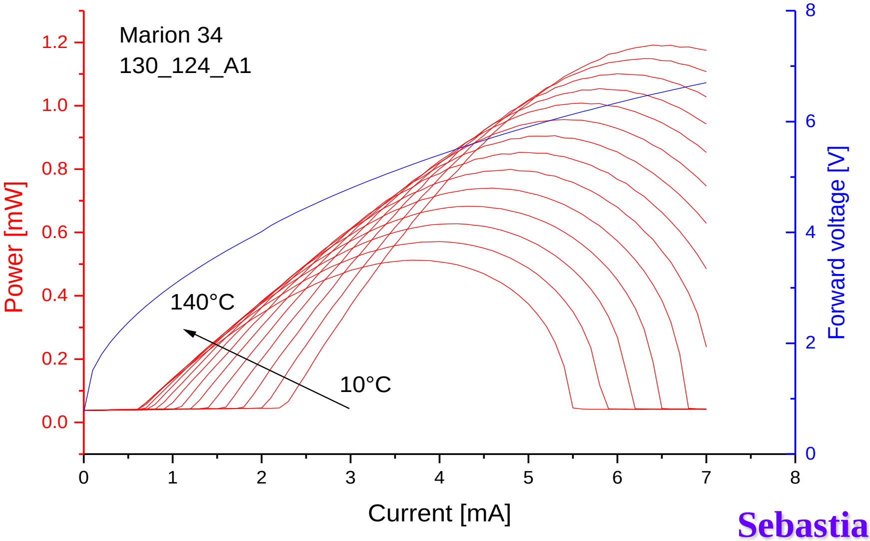
Schematic illustration of the principle of the dielectric mirror with many low and high refractive index layers and its reflectance.

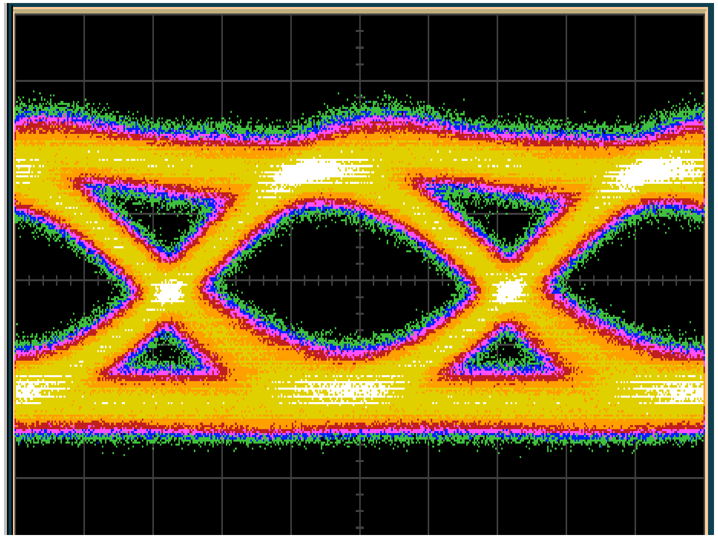
10 Gb/s 1.3-μm InGaAs/GaAs VCSELs fabricated at KTH



Performance at 10-140°C:

- **Wavelength: 1265-1280 nm**
- **SM across whole current range**
- **SMSR > 30dB**
- **Output power > 0.5mW**
- **Threshold Current < 2mA**
- **10 Gbit/s data transmission**





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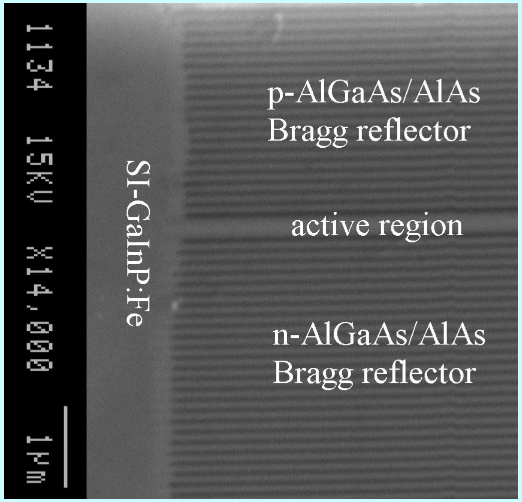
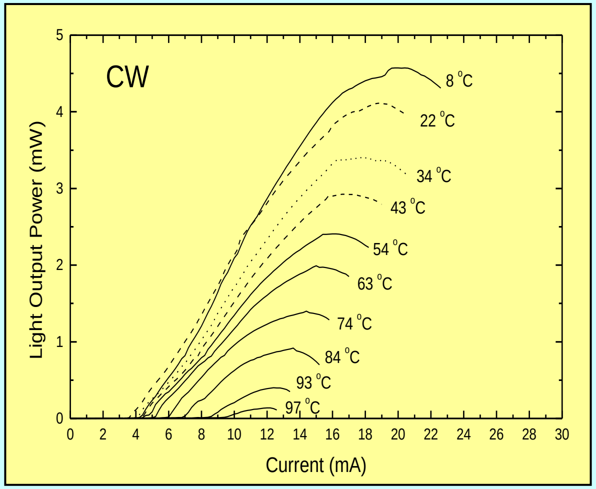
BH-VCSELs fabricated at KTH

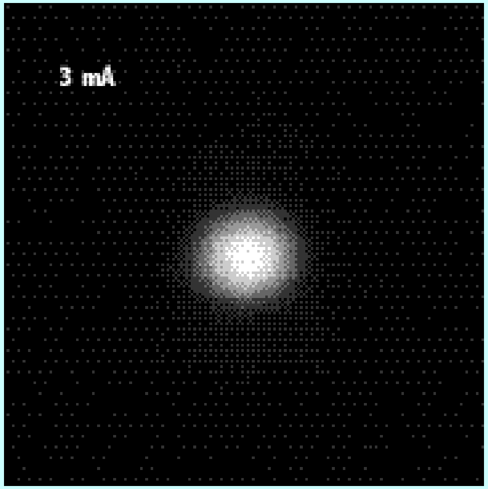
GaAs/AlGaAs BH-VCSELs with SI-GaInP Regrowth



Regrowth by *Hydride Vapour Phase Epitaxy*



***CW operation* up to 97°C**



***Single mode operation* up to 0.7 mW**

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