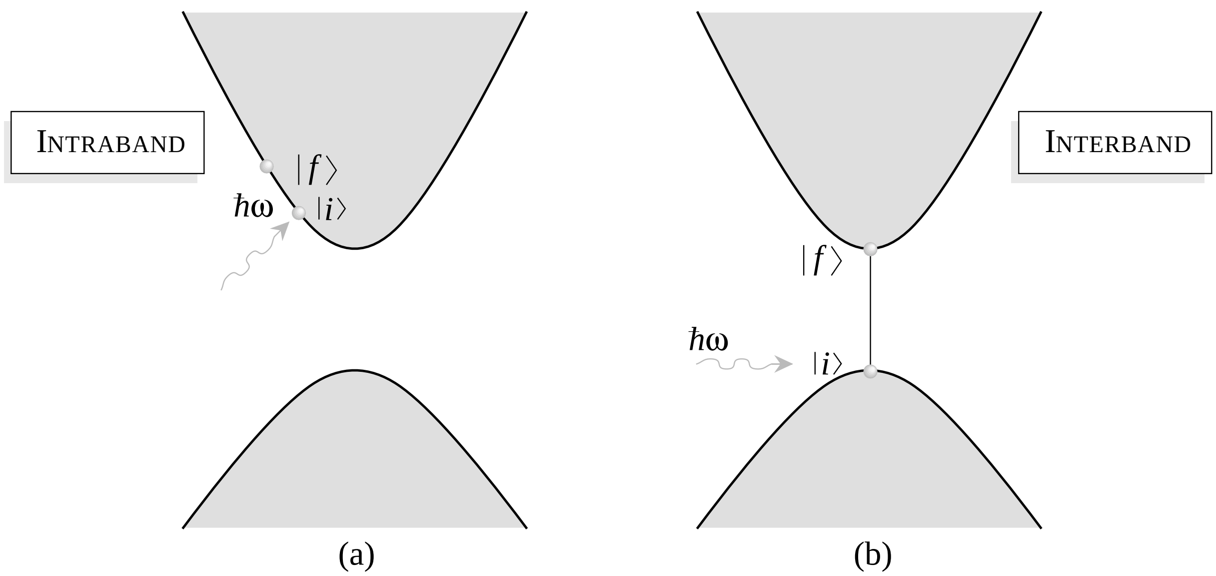
Chapter 9

OPTICAL PROPERTIES OF SEMICONDUCTORS



Intraband and interband scattering of an electron from an initial state k_i to a final state k_f.

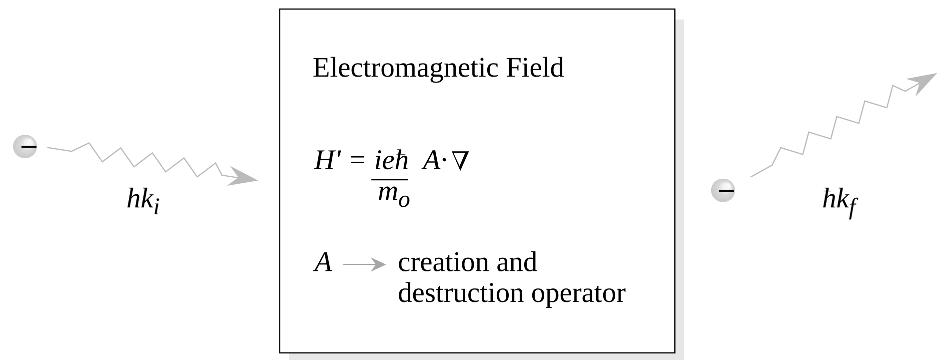
ELECTRONS IN ELECTROMAGNETIC FIELD: PERTURBATION

$$H = H_0 + H'$$

$$H_0 = \frac{-\hbar^2}{2m_o} \nabla^2 + V(r)$$ ➨ Bandstructure

To first order:

$$H' = \frac{ie\hbar}{m_o} A \cdot \nabla$$



A schematic of the scattering of an electron by the electromagnetic field.

Vector potential:

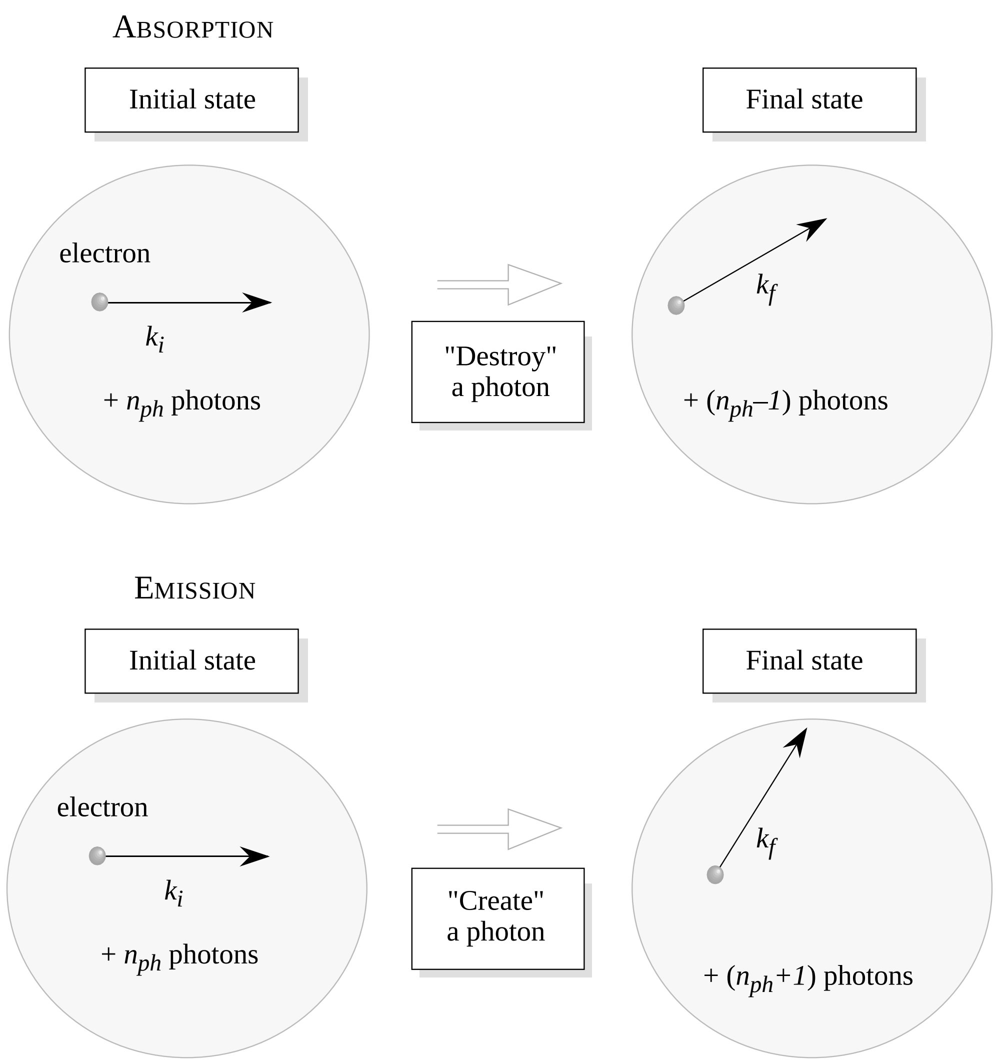
$$A = A_0 \exp i\omega t$$

$$A_0 = \sqrt{\frac{h}{2\omega\varepsilon V}}\,(b^\dagger + b)$$

$b^\dagger$: creation operator for photons

b: destruction operator for photons

Photon absorption and emission

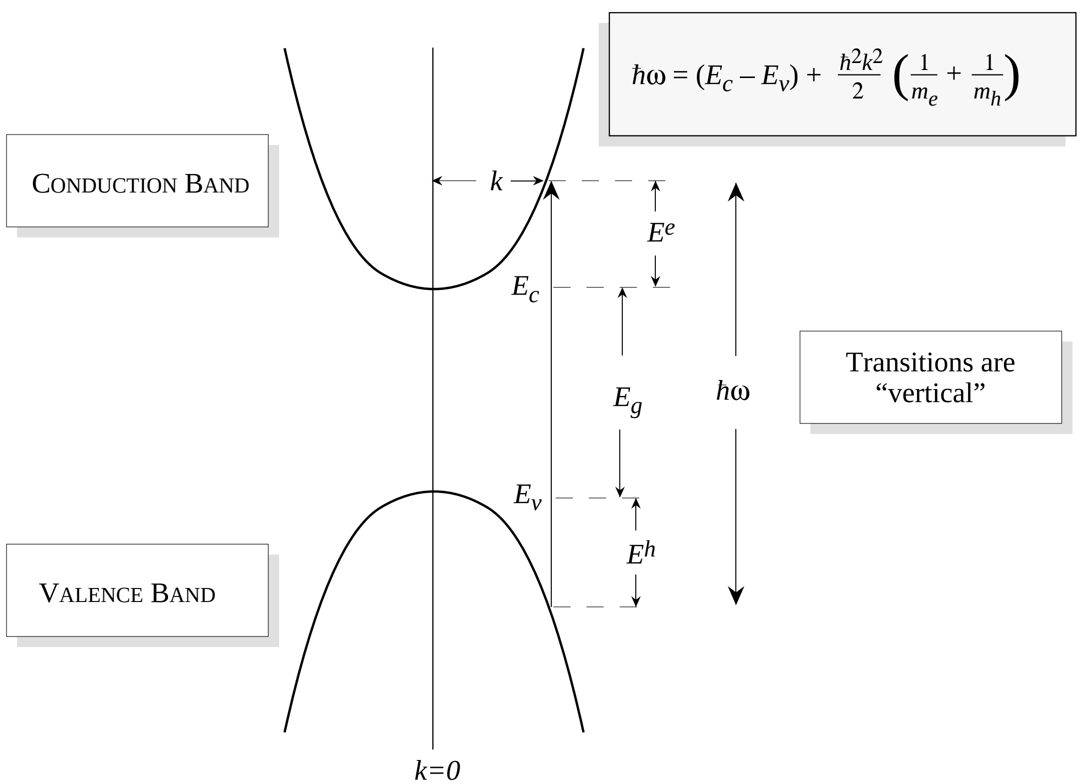


(a) Schematic of an absorption process where a photon is absorbed (destroyed) and the energy and momentum of the electron is altered.
(b) The emission of a photon where a photon is created.

STIMULATED AND SPONTANEOUS PROCESSES

Absorption of photons ➨ proportional to photon number n_{ph}
Emission of photons ➨ proportional to $(n_{ph} + 1)$
Stimulated process $\propto n_{ph}$
Spontaneous process $\propto 1$

Band to band processes in semiconductors ➨ "vertical" transitions in k-space



The positions of the electron and hole energies at vetical k-values. The electron and hole energies are determined by the photon energy and the carrier masses. Since the photon momentum is negligible the transitions are vertical.

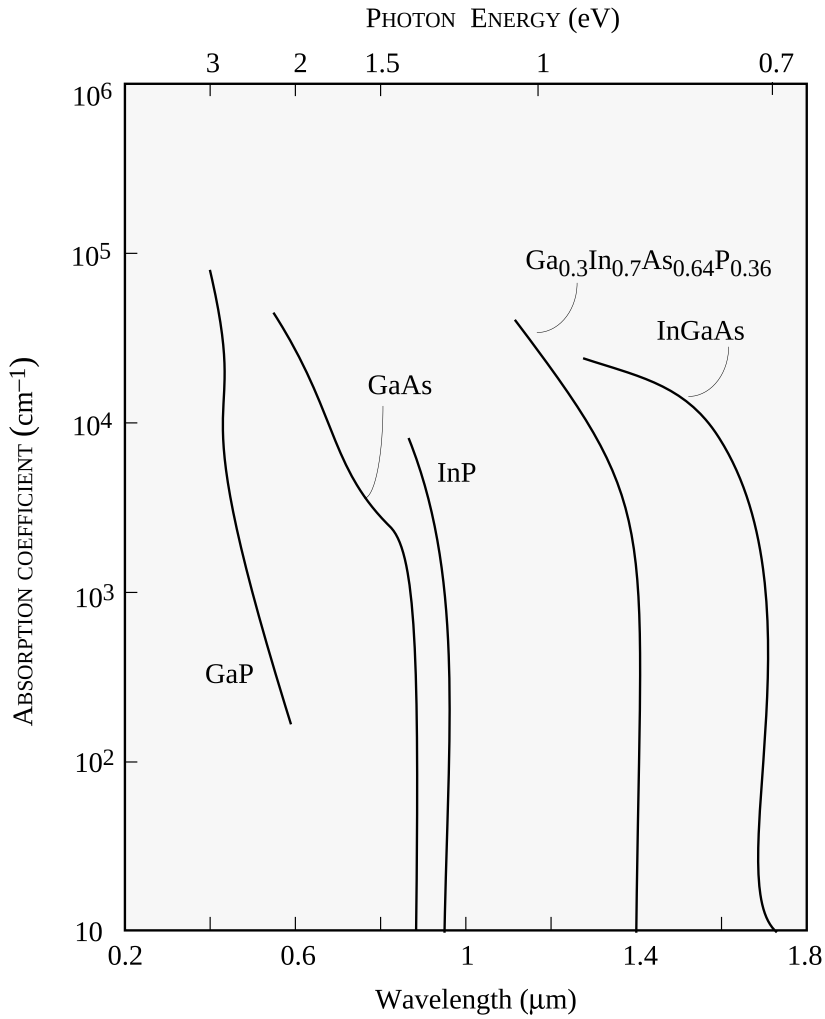
BULK SEMICONDUCTORS: BAND TO BAND ABSORPTION

Absorption rate:

$$W_{abs} = \frac{\pi e^2 \hbar n_{ph}}{2\varepsilon m_0 \hbar\omega} \left(\frac{2p_{cv}^2}{m_0}\right) \frac{2}{3} \; N_{cv}(\hbar\omega)$$

Absorption coefficient:

$$\propto \; = \frac{W_{abs}}{v n_{ph}}$$



Absorption coefficient for several semiconductors.

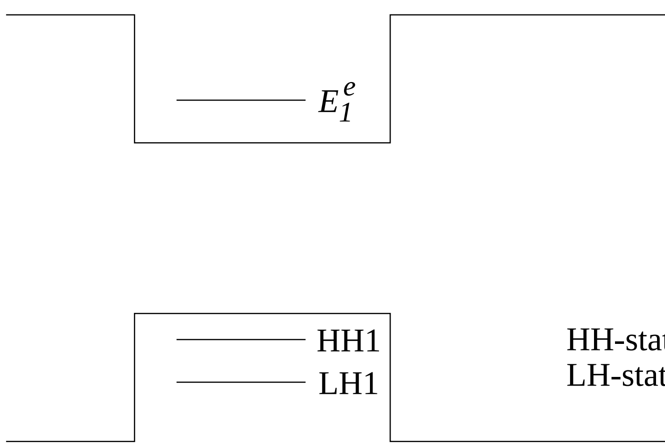
INTERBAND OPTICAL PROCESSES IN QUANTUM WELLS

Quantum wells (and strain) alter the cubic symmetry of fcc based structures and makes the optical transitions' polarization sensitive. For confinement along (001) direction:

z-polarized light: HH → c-band: No coupling
LH → c-band: $|\mathbf{p}_{if}|^2 = 2/3|\langle p_x|p_x|s\rangle|^2$

x-polarized light: HH → c-band: $|\mathbf{p}_{if}|^2 = 1/2|\langle p_x|p_x|s\rangle|^2$
LH → c-band: $|\mathbf{p}_{if}|^2 = 1/6|\langle p_x|p_x|s\rangle|^2$

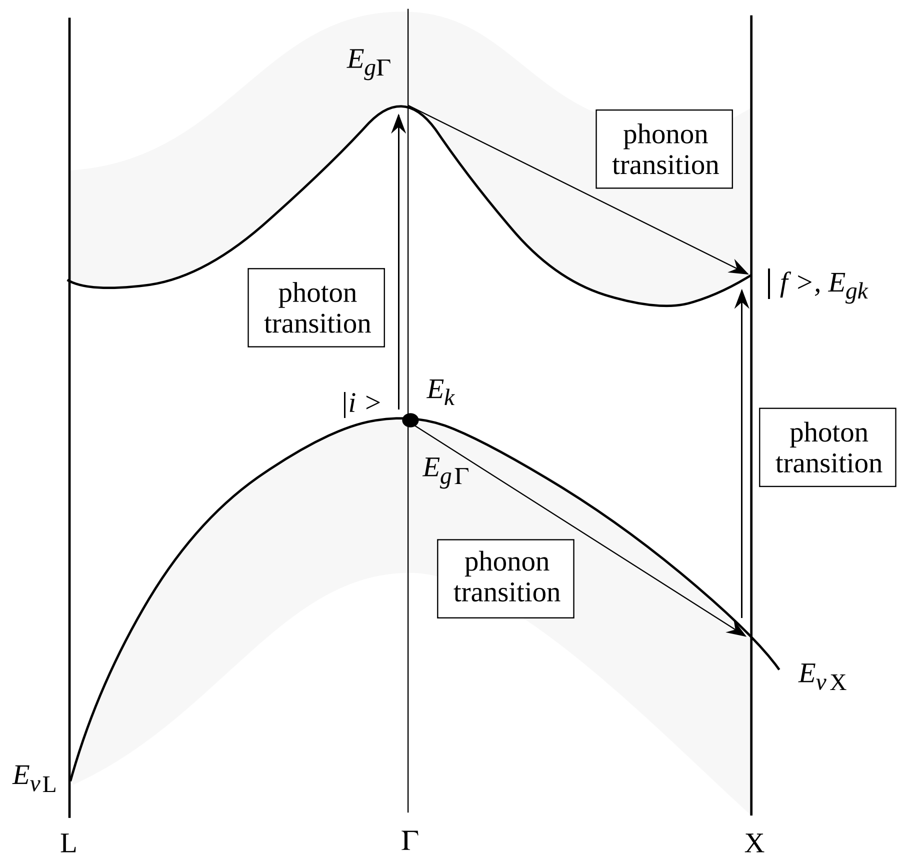
y-polarized light: HH → c-band: $|\mathbf{p}_{if}|^2 = 1/2|\langle p_x|p_x|s\rangle|^2$
LH → c-band: $|\mathbf{p}_{if}|^2 = 1/6|\langle p_x|p_x|s\rangle|^2$



HH-state $|3/2, \pm 3/2\rangle$
LH-state $|3/2, \pm 1/2\rangle$

INTERBAND TRANSITIONS IN INDIRECT GAP MATERIALS

Due to momentum conservation requirements (photon momentum is essentially zero) first order transitions in indirect gap materials are forbidden. Second order transitions involving phonons or impurities are allowed.



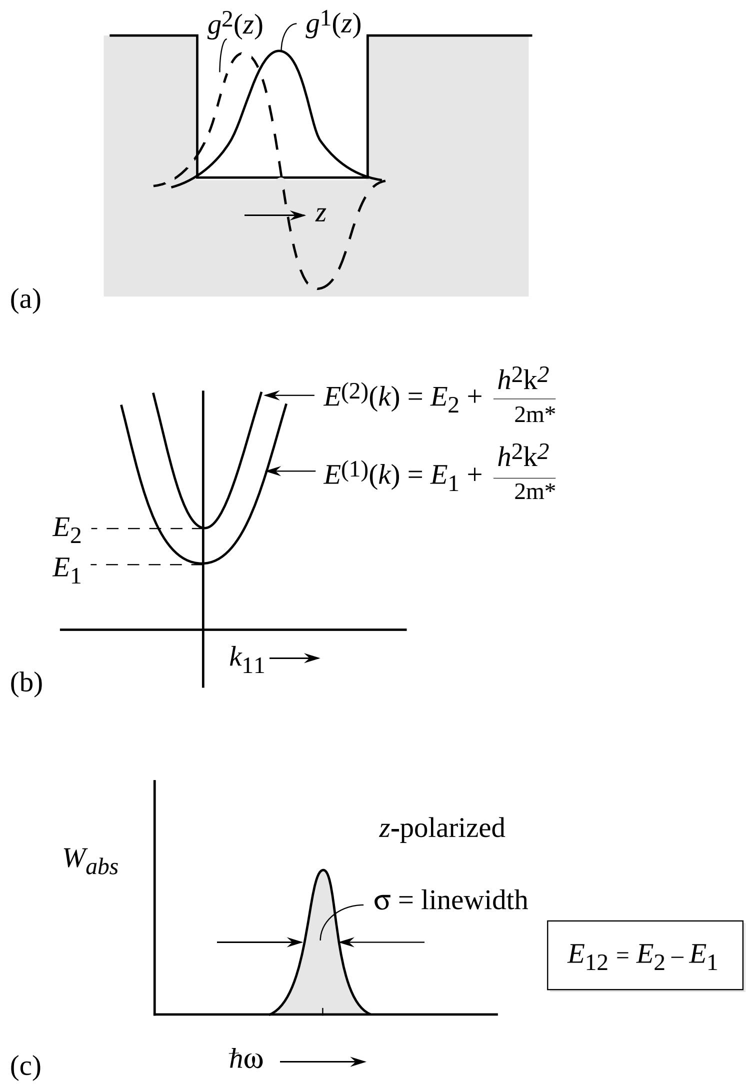
Two processes showing how a photon and a phonon can take an electron from state $|i>$ to state $|f>$. The photon energy need not be equal to the vertical energy, since the intermediate transitions are "virtual," i.e., the electron does not reside there for any length of time.

Much smaller absorption coefficient:

$$\propto \text{(indirect)} \sim \propto \text{(direct)} \times \frac{\langle \Delta u \rangle}{E_g}$$

INTERSUBBAND TRANSITIONS IN QUANTUM WELLS

Intersubband transitions are allowed in quantum wells (dots) and can be used for long wavelength detection.



Schematic presentation of the (a) envelope functions for two levels in a quantum well, (b) subband structure in the well, and (c) absorption rate for *z*-polarized light in a quantum well.

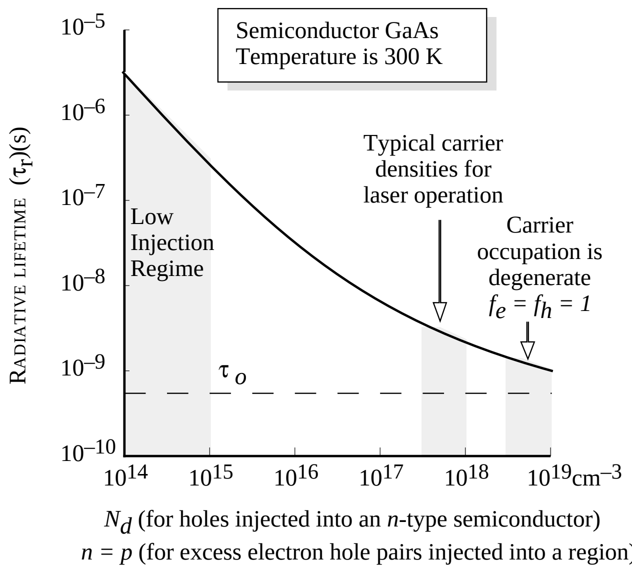
Symmetry based selection rules apply: Conduction band states have *s*-type central cell character ➠ only light polarized along *z*-axis can cause transitions, i.e., light has to travel in the plane of the quantum well.
In quantum dots intersubband transitions normal incidence absorption is allowed.

CARRIER INJECTION AND LIGHT EMISSION

Excess electrons and holes in semiconductor will recombine to create photons

A radiative lifetime for carriers can be defined by the relation

$$R_{spon} = \frac{\Delta n}{\tau} \text{ or } \frac{\Delta p}{\tau}$$



The dependence of the radiative lifetime in GaAs as a funciton of carrier injection *(n = p)* or minority carrier injection into a doped region with doping density as shown.

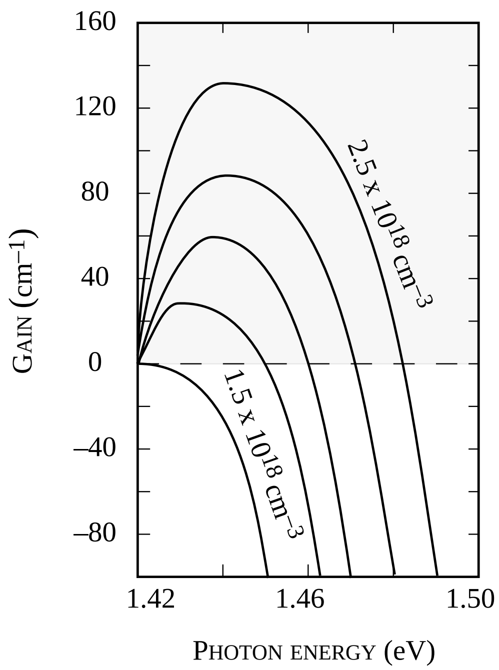
OPTICAL GAIN IN SEMICONDUCTORS

gain = emission coefficient – absorption coefficient

$$\propto f^e(E^e) + f^h(E^h) - 1$$

Propagation of an optical wave in a medium with a gain of

$$I(z) = I_o \exp(gz)$$

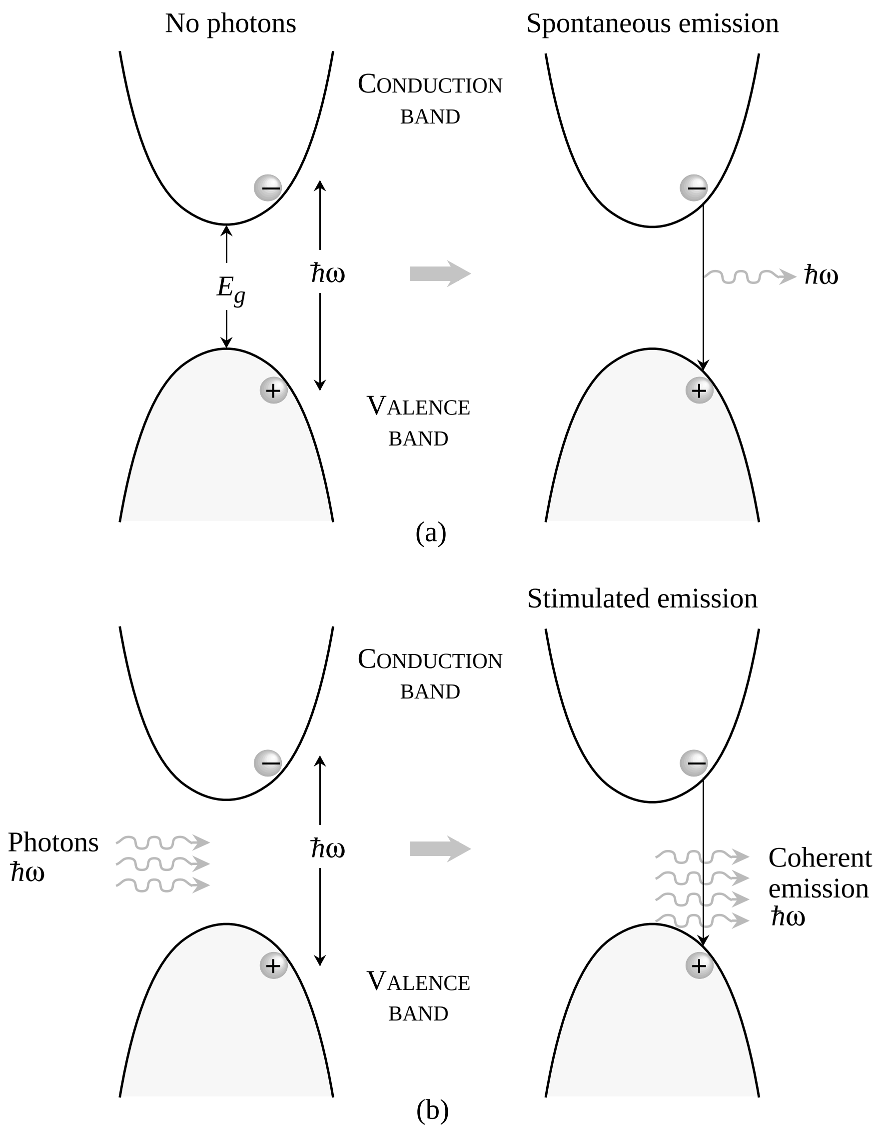


Gain vs. photon energy curves for a variety of carrier injections for GaAs at 300 K. The electron and hole injections are the same. The injected carrier densities are increased in steps of 0.25×10^{18} cm^{-3} from the lowest value shown.

LIGHT EMITTERS: LEDS AND LASER DIODES

LEDs: Emit light by spontaneous emission

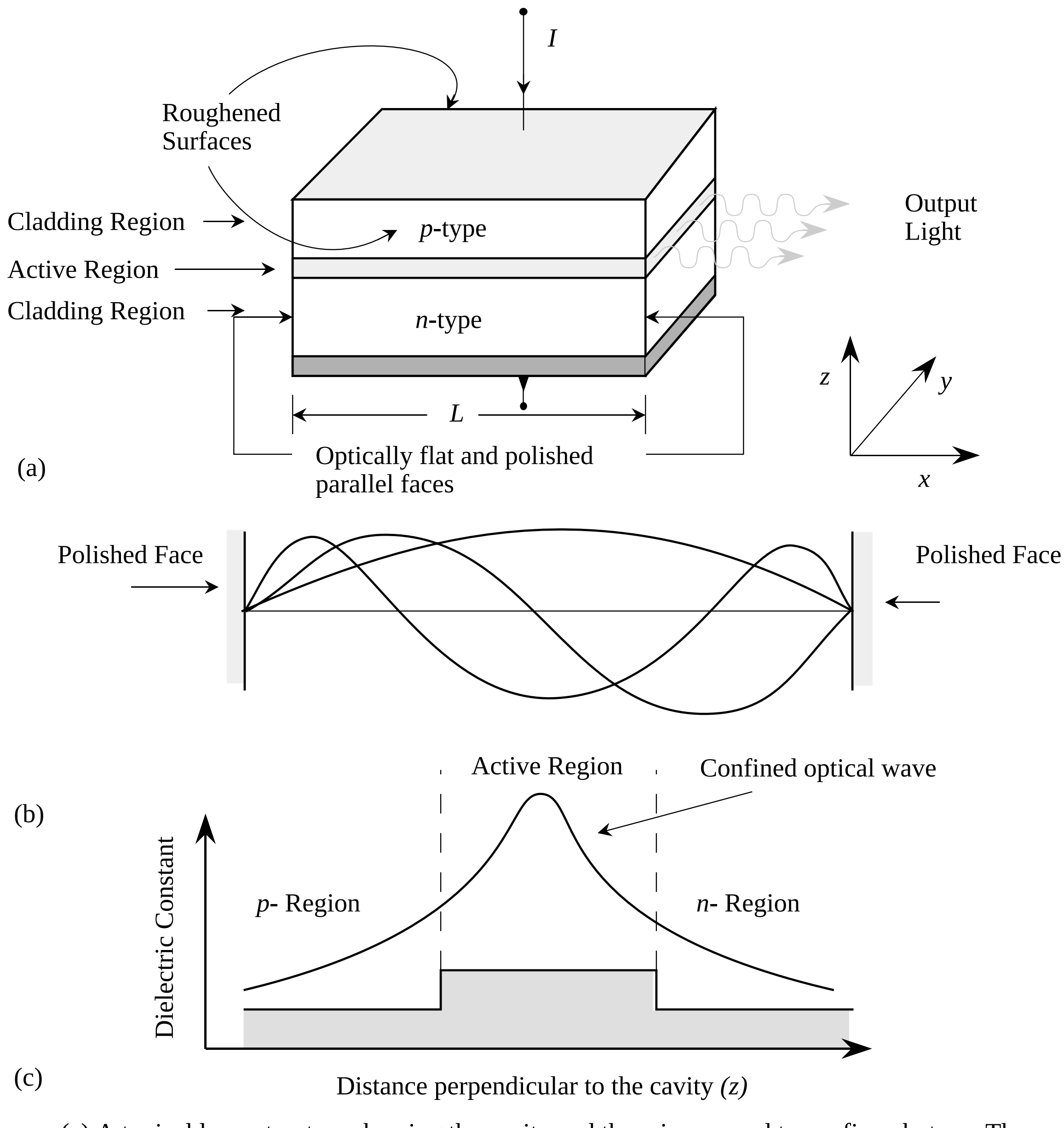
Laser diodes: Emit light through stimulated emission



(a) In the absence of any photons, electron-hole recombination produces photons with no phase coherence. (b) In the presence of photons, electron-hole recombination produces photons which are coherent with the previously existing photons.

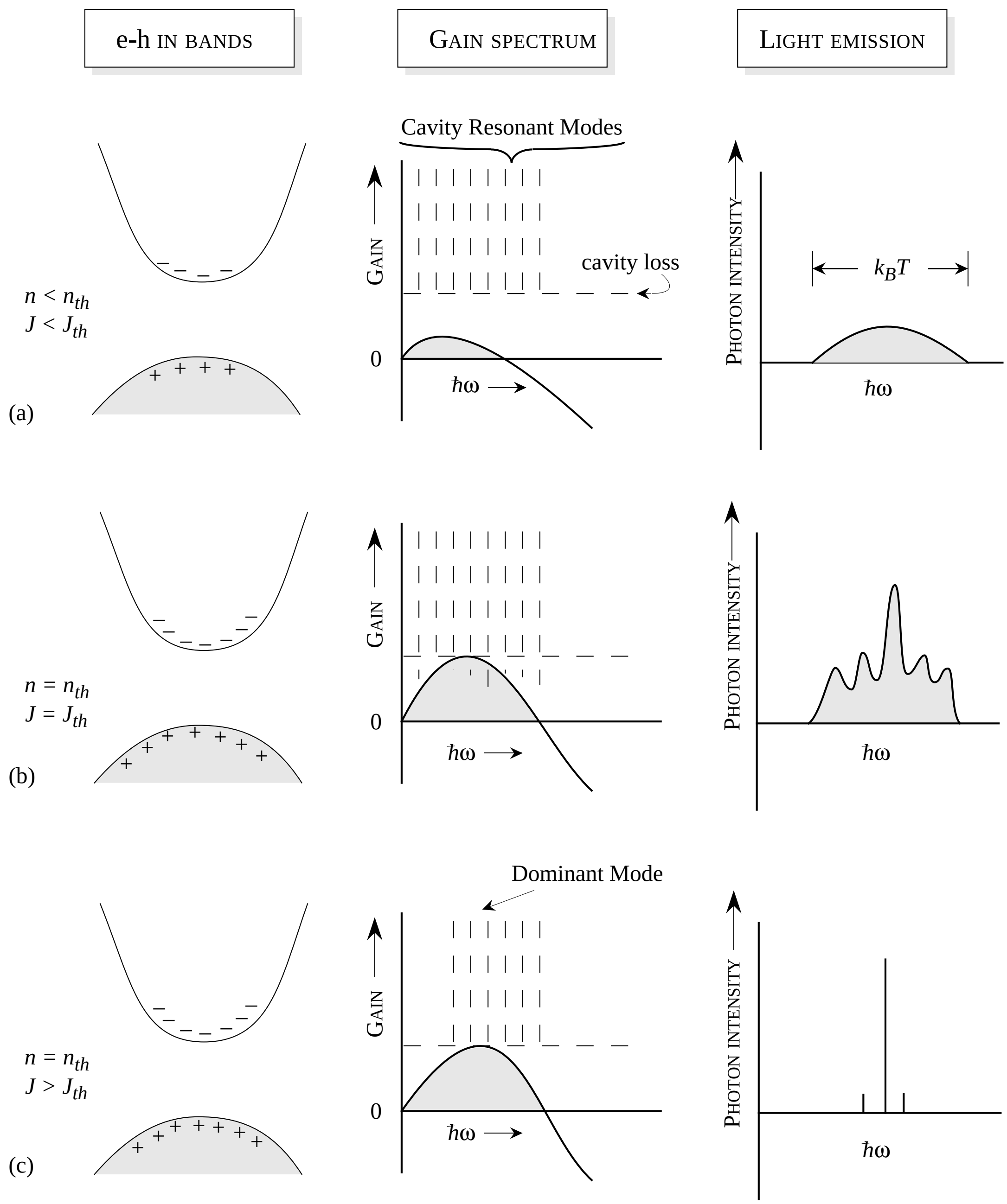
TYPICAL LASER DIODE STRUCTURE

- Gain region for photon generation
- Waveguide region to guide the optical wave
- Mirrors to provide feedback



(a) A typical laser structure showing the cavity and the mirrors used to confine photons. The active region can be quite simple as in the case of double heterostructure lasers or quite complicated as in the case of quantum well lasers. (b) The stationary states of the cavity. The mirrors are responsible for these resonant states. (c) The variation in dielectric constant is responsible for the optical confinement.

LASER DIODE: OPTICAL OUTPUT



(a) The laser below threshold. The gain is less than the cavity loss and the light emission is broad as in an LED. (b) The laser at threshold. A few modes start to dominate the emission spectrum. (c) The laser above threshold. The gain spectrum does not change, but, due to the stimulated emission, a dominant mode takes over the light emission.

LONG WAVELENGTH LASERS

Staggered band offset quantum wells can be used to make longwavelength devices.