Radiative and Nonradiative Recombination

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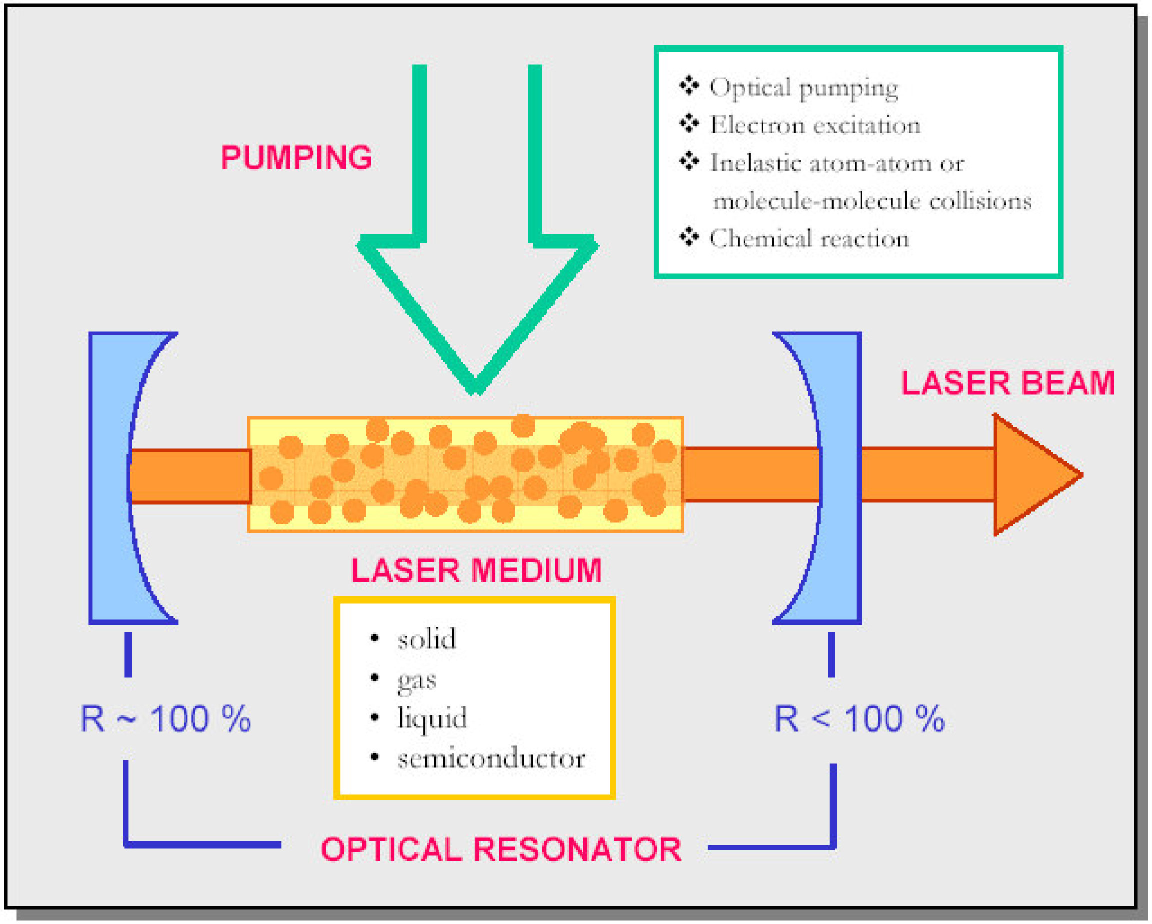
Laser Principle



Requirement for Semiconductor Laser

- **Gain Medium**

  Semiconductor material

- **Optical Feedback**

  Cleaved Facets (Fabry-Perot cavity)

- **Mode Confinement**

  Dielectric Waveguiding

- **Optical Gain**

  Electrical/optical pumping

Definition of Recombination

- A process whereby electrons and holes (carriers) are annihilated or destroyed.
- Reversed process is **Generation**: A process whereby electrons and holes are created.
- Classification:
  - A. Radiative Recombination: Photon
  - B. Nonradiative Recombination: Phonon or Lattice vibration

Radiative Recombination

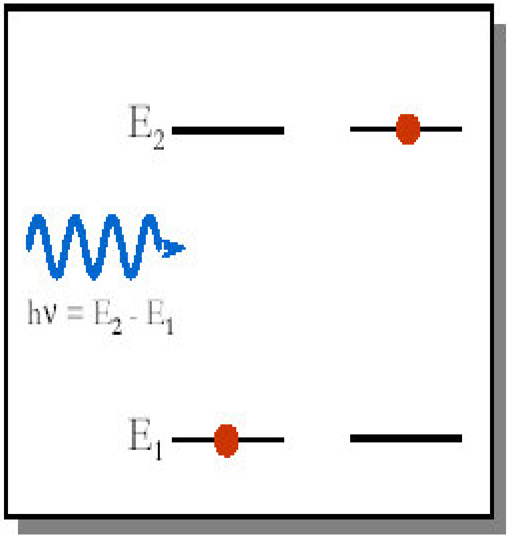
- Radiative Recombination occurs when an electron in the conduction band recombines with a hole in the valence band and the excess energy is emitted in the form of a photon.
- Optical processes associated with radiative transitions are:

  A. spontaneous emission

  B. absorption or gain

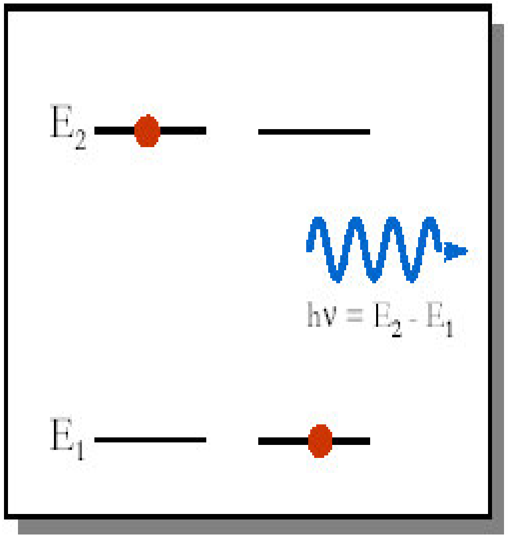
  C. stimulated emission

Radiative Transitions Processes



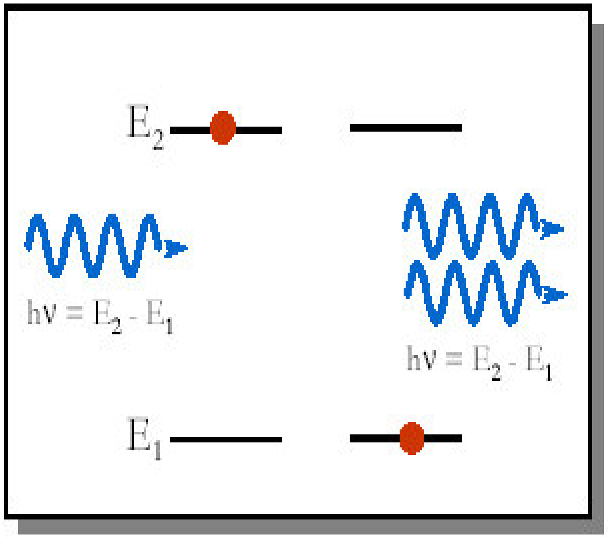
Absorption

- ✓ transition probability B_{12}



Spontaneous emission

- ✓ transition probability A_{21}
- ✓ random phase and direction



Stimulated emission

- ✓ transition probability B_{21}
- ✓ has the same frequency and phase as the incident light $\Rightarrow$ **light amplification**

Important Terms

- **Transparency**

  As pump rate increases, E_{fc} increases and E_{fv} decreases, the semiconductor becomes transparent at

  $$E_{fc} - E_{fv} = E_g$$

- **Optical gain**

  Difference between the stimulated emission and the absorption rate.

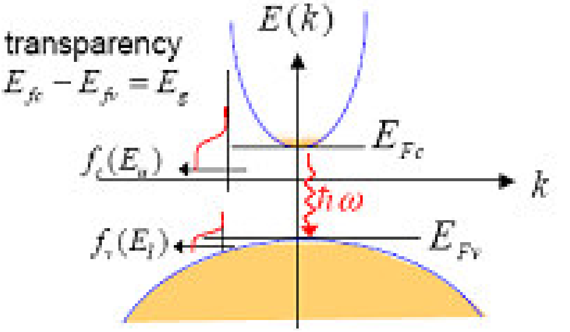
  $$E_{fc} - E_{fv} > E_g$$

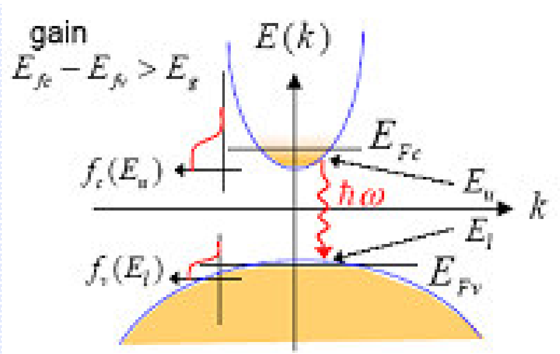
- **Threshold current (I_{th})**

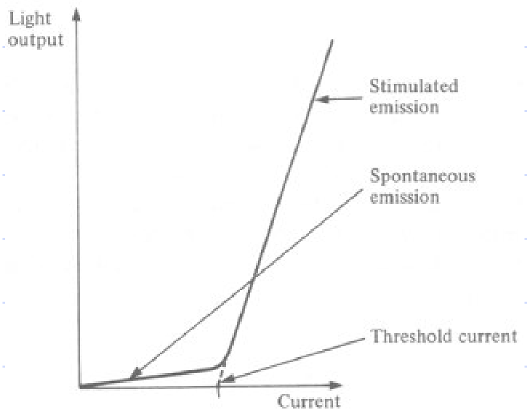
  The lowest current at which stimulated emission exceeds spontaneous emission.

  Below I_{th}, output mainly consists of spontaneous emission

  Above I_{th}, stimulated emission begins to dominate







Spontaneous Emission Rate

- Spontaneous emission rate increases when high enough (threshold) carrier density is injected into material to achieve optical gain.
- For every spontaneous photon emitted, A new carrier must be injected into the active region.
- Spontaneous emission contributes to threshold current, esp. in short-wavelength material.
- The total spontaneous emission rate per unit volume:

$$R(E) = \frac{4\pi q^2 \mu E}{m_0^2 \varepsilon_0 c^3 h^2} \int_{-\infty}^{\infty} \rho_c(E')\, \rho_c(E'')\, f_c(E')\, f_v(E'') \left| M_{if} \right|^2 dE'$$

Where E″ = E′ - E

Radiative Current Density

- Spontaneous emission rate can be approximated by

$$R = Bnp$$

where B: radiative recombination coefficient.

n and p: electron and hole density respectively.

- The current density due to spontaneous emission alone:

$$J_r = qdR$$

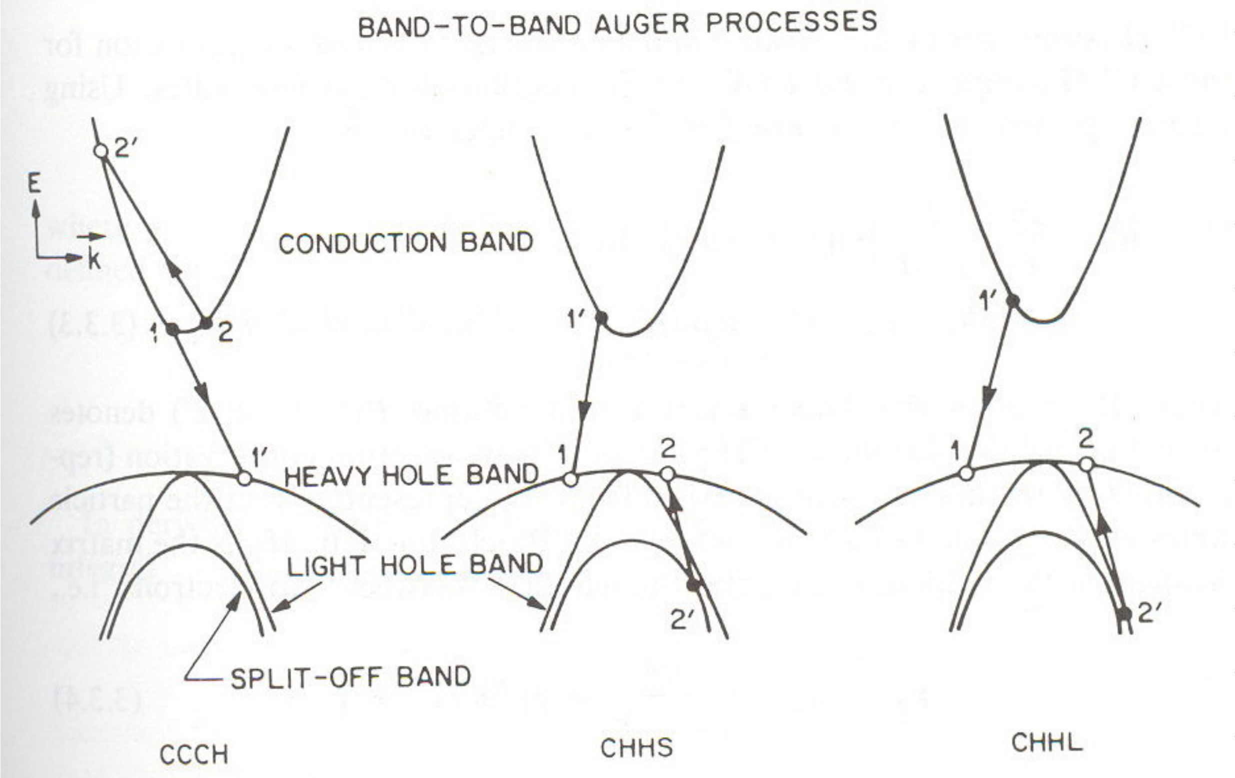
where d: active-layer thickness.

Nonradiative Recombination

- An electron in the conduction band recombines with a hole in the valence band and the excess energy is emitted in the form of heat in the semiconductor crystall lattice.
- Characterized by the absence of any useful emitted photons in the recombination process.
- Affecting performance of injection laser by increasing the threshold current
- Nonradiative Recombination processes include:
    - A. Auger Recombination
    - B. Surface Recombination
    - C. Recombination at defects

Auger Recombination

- Generally the predominant nonradiative mechanism
- Involving 4 particle states (CCCH, CHHS, CHHL)



Three different band to band Auger process

Auger Recombination Rate

- Representative values at room temperature:

  $C = 2 \sim 3 \times 10^{-29}$ cm^6/s (bulk 1.3um InGaAsP)

  $C = 7 \sim 9 \times 10^{-29}$ cm^6/s (bulk 1.55um InGaAsP)

  $C = 4 \sim 5 \times 10^{-30}$ cm^6/s (bulk GaAs)

  Auger Recombination rate is not well characterized for other material systems.

- Difficulty with Auger recombination:

  A. Accurate information of the band structure at more than a bandgap away from the band edge must be known.

  B. Overlap integrals of "k-space distant" Bloch functions must also be known.

- Theories are inevitably made very simplifying assumptions.

Nonradiative Recombination Current Density

- Auger Recombination rate (approximately)

$$R_a = Cn^3$$

Where C: Auger coefficient

n: injected carrier density

- Defect and Surface Recombination rate

$$R_d = A_{nr} n$$

Where A_{nr}: Trap and surface recombination coefficient

- The current density due to Nonradiative Recombination :

$$J_{nr} = qd\,(R_a + R_d) = qd\,(Cn^3 + A_{nr}n)$$

Threshold Current Density

- Total threshold current density:

$$J_{th} = qd\,(A_{nr} n_{th} + Bn_{th}^{2} + Cn_{th}^{3}) + J_L$$

where n_{th}: the injected carrier density at threshold

J_L : the leakage current density

- For good quality laser, e.g. InGaAsP, the first term is negligible,

$$J_{th} \cong qd\,(Bn_{th}^{2} + Cn_{th}^{3}) + J_L = J_r + J_{nr} + J_L$$

where

$$J_r = qd\,(Bn_{th}^{2}) = qdR$$

$$J_{nr} = qd\,(Cn_{th}^{3}) = qdR_a$$

Heterojunction Carrier Leakage

- Caused by diffusion and drift of electrons and holes from the edges of the active region to the cladding layers.
- Must be considered under high temperature or material systems which do not have the luxury of large heterobarriers.
- Calculation: find the minority carrier density spill over the active layer into the cladding layer interface, then find the diffusion and drift currents.

Leakage Current Density

- Electron leakage current:

$$J_n = qD_n N_{p0} [\sqrt{\frac{1}{L_n^2} + \frac{1}{L_{nf}^2}} \coth \sqrt{\frac{1}{L_n^2} + \frac{1}{L_{nf}^2}} x_p + \frac{1}{L_{nf}}]$$

where D_n: minority electron diffusion τ_n coefficient
N_{p0}: electron population at the edge of p-cladding
L_n: minority electron diffusion length
L_{nf}: drift length

- In quantum well laser, it can be approximated to:

$$J_L = qd\frac{N}{\tau_n}$$

where τ_n: minority carrier lifetime
d: active layer thickness

Temperature Dependence of J_{th}

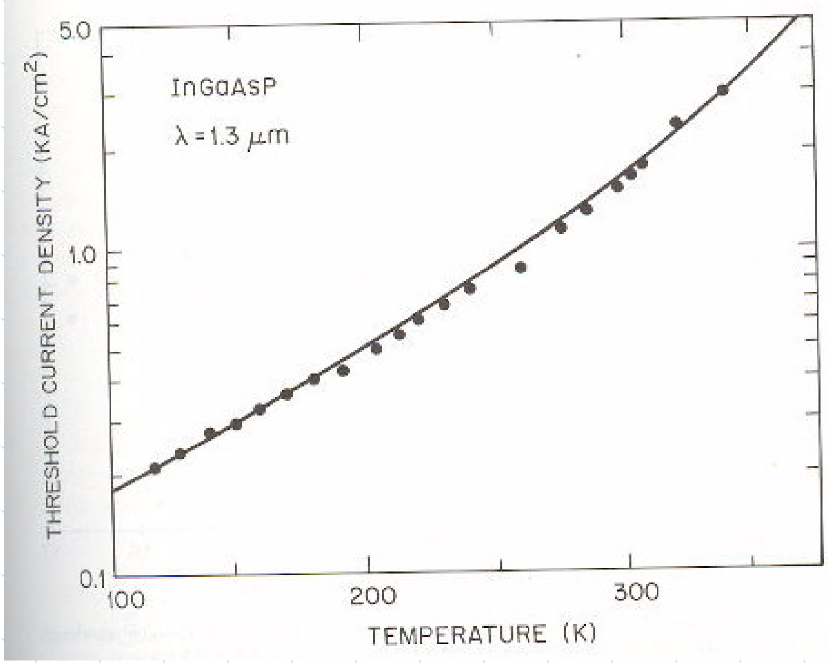
◆ For double-heterostructure lasers:

$$I_{th}(T) = I_0 \exp(T / T_0)$$

where T0 : characteristic temperature

High temperature dependence of Jth of InGaAsP Laser

- Heterobarrier leakage
- Auger Recombination
- Intervalence band absorption



Measured J_{th} as a fun. Of temperature for a 1.3 um InGaAsP-InP laser

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