The three basic transition processes between two energy levels $E_1$ and $E_2$

The black dots indicate the state of the atom

a) Absorption
b) Spontaneous Emission
c) Stimulated Emission
Basic structure of a junction semiconductor laser in the form of a Fabry-Perot cavity
Comparison between some characteristics of different laser structures:

Homojunction | Single Heterostructure | Double Heterostructure

- **Energy Levels**
  - Homojunction: Single energy level
  - Single Heterostructure: Multiple energy levels
  - Double Heterostructure: Multiple energy levels

- **Refractive Index**
  - Homojunction: Constant refractive index
  - Single Heterostructure: Two distinct refractive index regions
  - Double Heterostructure: Three distinct refractive index regions

- **Light Absorption**
  - Homojunction: Uniform light absorption
  - Single Heterostructure: Gradual light absorption change
  - Double Heterostructure: Sharp light absorption change
Threshold current density versus temperature for three laser structures.
Typical three-layer dielectric waveguide showing ray trajectories for total internal reflection confinement of the guided wave.
Cartesian coordinate system relative to the edge-emitting laser
Compositional dependence of an AlGaAs energy gap and refractive index. Note that the direct bandgap occurs only over mole fractions up to $x=0.4$ (Al).

Bandgap can be given by:

$$E_g(x) = 1.424 + 1.247x \quad \text{(eV)}$$

For $\text{Al}_x\text{Ga}_{1-x}\text{As}$
(Electric field)$^2$ as a function of position within the double-heterostructure waveguide for $d=0.2$ microns for different AlAs mole fractions
(Electrical field)² for different thickness core layers, showing the confinement of light with cladding of x=0.3 AlAs
(Electric field)$^2$ as a function of the order of the modes. Distribution for fundamental, first, second-order modes. Note that this waveguide is 1 micron thick and supports several modes.
Confinement factor for the fundamental mode as a function of the active layer thickness and the alloy composition for a AlGaAs/GaAs symmetric three-layer waveguide
Schematic of the far-field emission of a stripe laser made from a double heterostructure. Note that the diffraction is larger in the vertical direction due to the asymmetry of the slab waveguide.
Diffraction angle as a function of active layer thickness and composition of the waveguide cladding layers of stripe laser
Two methods for the construction of a “gain-guided” double heterostructure laser: Oxide isolation and proton bombardment
Schematic of the gain-guided stripe laser. The refractive index is slightly higher in the area through which the current flows, and thus a optical waveguide is also established in the lateral direction. This essentially decreases the volume of the laser which has to be pumped, and thereby the threshold current.
Waveguiding is established by changing the complex dielectric constant in the stripe through changes in the carrier density, and this influences the electric field intensity. The wave equation can be written:

$$\nabla^2 \varepsilon_y + \left(k_0^2 \varepsilon/\varepsilon_0\right) \varepsilon_y = 0.$$ 

The wave equation with a sinusoidal time dependence given by $\exp(j\omega t)$

$$\varepsilon(x, y)/\varepsilon_0 = \left[\varepsilon(0) - a^2 y^2\right]/\varepsilon_0$$

since $k_0 = 2\pi/\lambda$ and $\varepsilon/\varepsilon_0$ is taken as 2-Dimensional

This is the dielectric permittivity in the pumped stripe

This is the dielectric permittivity outside of the stripe (unpumped)
Transverse modes within the waveguide as a function of the stripe width for planar stripe double heterostructure lasers.
Energy versus density of states in a semiconductor:

At equilibrium (0K) inverted (0K) inverted (T>0K)

Fig. 39  Energy versus density of states in a semiconductor. (a) Equilibrium, $T = 0$ K. (b) Inverted, $T = 0$ K. (c) Inverted, $T > 0$ K. (After Nathan, Ref. 53.)
The rate of photon emission at $\hbar \nu$ due to a transition from a group of upper states near $E$ in the conduction band to lower states at the $E-h\nu$ in the valence band. The rate for this emission is proportional to the product of the density of the occupied upper states $n_c(E)F_c(E)$ and the density of unoccupied lower states $n_v(E-h\nu)[1-F_v(E-h\nu)]$. The total emission rate is obtained by integrating over all energies:

$$W_{\text{spont}}(h\nu) = B \int n_c(E)n_v(E - h\nu)F_c(E)[1 - F_v(E - h\nu)]|\langle M \rangle|^2 \, dE. \quad (47)$$

In a similar manner we can write

$$W_{\text{absorption}}(h\nu) = B \int n_v(E - h\nu)n_c(E)F_v(E - h\nu)[1 - F_c(E)]|\langle M \rangle|^2 \, dE. \quad (48)$$

For the emission rate

For the absorption rate
Energy versus density of states diagram where both conduction and valence bands have band tails.

Fig. 40  Energy versus density of states where both conduction and valence bands have band tails. (After Halperin and Lax, Ref. 55.)
Variation of the gain coefficient with the normal current density. The dashed line represents a linear dependence.
Threshold current density of a laser

Threshold occurs when the gain satisfies the condition that a light wave makes a complete transversal of the cavity without attenuation:

\[ R_{\text{exp}}[(\Gamma g - \alpha)L] = 1 \]

where \( \Gamma g(\text{threshold gain}) = \alpha + \frac{1}{L} \ln(1/R) \)

\[ J_{\text{th}}(\text{A/cm}^2) = \frac{J_0 d}{\eta} + \frac{J_0 d}{g_0 \eta \Gamma} \left[ \alpha + \frac{1}{L} \ln \left( \frac{1}{R} \right) \right]. \]
Comparison between calculated and experimental threshold current densities for a InGaAsP laser
Fig. 43  Schematic representation of energy bandgap, refractive index, and light intensity for three heterostructure lasers. (a) Separate confinement. (b) Large optical cavity. (c) Four-layered. (After Burrus, Casey, and Li, Ref. 60.)
These are the different methods with which lateral waveguide geometries can be made and the stripe can be pumped.

Fig. 44 Cross-sectional views of various heterostructure lasers.
Threshold current density and lasing wavelength as a function of the junction temperature.

Schematic of a DFB (distributed feedback) laser, commonly used for telecommunication sources.
Square well potential for a quantum well heterostructure. The density of states from such a system gives characteristic steps.
Measurement of light output from a packaged laser showing the DH laser performance at room temperature.
Temperature dependence of the threshold current of a DH laser

Light output versus current curves (L-I) for a laser as a function of temperature

Temperature dependence of the threshold current of a DH laser
Emission spectra of a diode laser below, just at, and above threshold indicating the narrowing of the emission when lasing occurs.
High resolution emission spectra of a DH laser (InP/InGaAsP) showing multi-longitudinal mode emission.
Mode selection for the longitudinal modes arises from the requirement that only an integral number (m) of half-wavelengths will fit between the reflection planes of an optical cavity.

For large m, the mode spacing is:

$$m\lambda = 2L\bar{n}$$

$$\Delta \lambda = \frac{\lambda^2 \Delta m}{2\bar{n}L[1 - (\lambda/\bar{n})(d\bar{n}/d\lambda)]}.$$
Relative emission intensity of GaAs DH laser operated at 300K, showing threshold current of 87 mA.
Time delay for laser $t_d$ for different currents

- $N_A = 2 \times 10^{17} \text{ cm}^{-3}$
- $N_A = 6.5 \times 10^{17} \text{ cm}^{-3}$
- $N_A = 2.5 \times 10^{18} \text{ cm}^{-3}$
- $N_A = 9 \times 10^{18} \text{ cm}^{-3}$
- $N_A = 2.7 \times 10^{19} \text{ cm}^{-3}$
- $T = 300 \text{ K}$

Graph showing the relationship between $I/(I-I_{th})$ and delay time $t_d$ (ns).
\[ \frac{dn}{dt} = \frac{I}{qAd} - \frac{n}{\tau_e} \]

\[ n(t) = \left(\frac{\tau_e I}{qAd}\right)\left[1 - \exp\left(-\frac{t}{\tau_e}\right)\right] \]

\[ t = \tau_e \ln\left[\frac{I}{I - qn(t)Ad/\tau_e}\right] \]

\[ t_d = \tau_e \ln\left(\frac{I}{I - I_{th}}\right) \]

For a current level \( I_0 < I_{th}, \) solving \( IADq \) gives

\[ t_d = \tau_e \ln\left[\left(\frac{I - I_0}{I - I_{th}}\right)\right] \]
Light output versus modulation frequency. The insert shows the laser cross-section:
Variation of the emission wavelength and threshold current density as a function of the temperature. This is for a PbTe/PbSnTe DH laser.
Threshold current as a function of operating time of a laser. This is for a InP/InGaAsP DH laser.
Microcavity lasers with diameters down to 1µm were first fabricated and electrically pumped over 10 years ago.

These lasers rapidly evolved into monolithic low-threshold lasers

J.L. Jewell, A. Scherer, S. McCall, J. Harbison
Commonly Used Laser Geometries

Edge emitting lasers:
- Emission parallel to the wafer surface.
- Light is reflected from cleaved facets.
- Length about 300 microns long.

Vertical cavity lasers:
- Emission perpendicular to the wafer.
- Need grown high reflectivity mirrors.
- Can be integrated into dense arrays.
- Size about 5 microns.
Vertical Cavity Surface Emitting Microlasers (VCSELs)

- Mirrors and active area are controlled by crystal growth
- Light emits perpendicular to the wafer surface
- Threshold currents as low as $10 \mu A$ have been reported
- VCSELs are presently used for fast optical interconnects
Ultra-small vertical cavity lasers

The mode volume can only be reduced to one cubic wavelength

Microdisk Lasers

Invented by McCall, Levy and Slusher (1992)

Light is confined to a thin slab, and reflected from the edge of a disk by total internal reflection

Laser size is limited by bend losses
Evolution of the design for ultra-small optical cavities

Thin slab to confine light in vertical direction

Using Bragg reflectors to make Fabry-Perot cavity
SOI wafer processing for amplifier electronics

Definition of high-Q optical cavity and undercut thermal isolation

Definition of lenses by back-side alignment
Deposit tungsten mirror layer stack

Fabricate 2-dimensional grating

Align lenses by back-side alignment