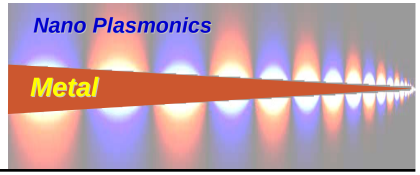
Nanophotonics



Nanophotonics, Paras N. Prasad, 2004, John Wiley & Sons, Inc., Hoboken, New Jersey., ISBN 0-471-64988-0

Table 2.1. Similarities in Characteristics of Photons and Electrons

Photons	Electrons
Wavelength	
$\lambda = \frac{h}{p} = \frac{c}{\nu}$	$\lambda = \frac{h}{p} = \frac{h}{mv}$
Eigenvalue (Wave) Equation	
$\left\{\nabla \times \frac{1}{\varepsilon(r)} \nabla \times\right\} \mathbf{B}(r) = \left(\frac{\omega}{c}\right)^2 \mathbf{B}(r)$	$\hat{H}\psi(r) = -\frac{\hbar^2}{2m}(\nabla \cdot \nabla + V(r))\psi(r) = E\psi$
Free-Space Propagation	
Plane wave $\mathbf{E} = (\frac{1}{2})\mathbf{E}^\circ(e^{i\mathbf{k}\cdot\mathbf{r}-\omega t} + e^{-i\mathbf{k}\cdot\mathbf{r}+\omega t})$ $\mathbf{k}$ = wavevector, a real quantity	Plane wave: $\Psi = c(e^{i\mathbf{k}\cdot\mathbf{r}-\omega t} + e^{-i\mathbf{k}\cdot\mathbf{r}+\omega t})$ $\mathbf{k}$ = wavevector, a real quantity
Interaction Potential in a Medium	
Dielectric constant (refractive index)	Coulomb interactions
Propagation Through a Classically Forbidden Zone	
Photon tunneling (evanescent wave) with wavevector, $\mathbf{k}$, imaginary and hence amplitude decaying exponentially in the forbidden zone	Electron-tunneling with the amplitude (probability) decaying exponentially in the forbidden zone
Localization	
Strong scattering derived from large variations in dielectric constant (e.g., in photonic crystals)	Strong scattering derived from a large variation in Coulomb interactions (e.g., in electronic semiconductor crystals)
Cooperative Effects	
Nonlinear optical interactions	Many-body correlation Superconducting Cooper pairs Biexciton formation

Both photons and electrons are elementary particles that simultaneously exhibit particle and wave-type behavior.

Photons and electrons may appear to be quite different as described by classical physics, which defines photons as electromagnetic waves transporting energy and electrons as the fundamental charged particle (lowest mass) of matter.

A quantum description, on the other hand, reveals that photons and electrons can be treated analogously and exhibit many similar characteristics.

Free-Space Propagation of photons and electrons

In a “free-space” propagation, there is no interaction potential or it is constant in space.
For photons, it simply implies that no spatial variation of refractive index *n* occurs.

The wavevector dependence of energy is different for photons (linear dependence) and electrons (quadratic dependence).

$$\omega = c|k| \qquad\qquad E = \frac{\hbar^2 k^2}{2m}$$

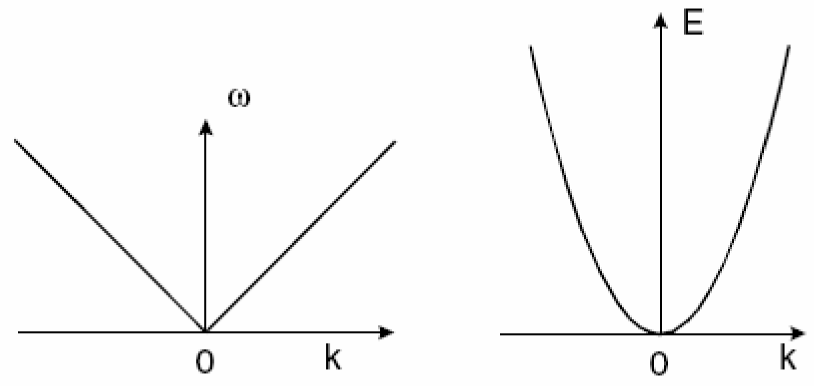


Figure 2.1. Dispersion relation showing the dependence of energy on the wavevector for a free-space propagation. (a) Dispersion for photons. (b) Dispersion for electrons.

For free-space propagation, all values of frequency for photons and energy *E* for electrons are permitted.
This set of allowed continuous values of frequency (or energy) form together a band,
and the band structure refers to the characteristics of the dependence of the frequency (or energy) on the wavevector **k.**

Confinement of Photons and Electrons

In the case of photons,
the confinement can be introduced by trapping light in a region of high refractive index or with high surface reflectivity.

The confinement of electrons also leads to modification of their wave properties and produces quantization
—that is, discrete values for the possible eigenmodes.

The field distribution and the corresponding propagation constant are obtained by the solution of the Maxwell's equation and imposing the boundary conditions (defining the boundaries of the waveguide and the refractive index contrast). The solution of the wave equation shows that the confinement produces certain discrete sets of field distributions called *eigenmodes, which are labeled by quantum numbers* (integer).

The corresponding wave equation for electrons is the Schrödinger equation. The potential confining the electron is the energy barrier—that is, regions where the potential energy *V is much higher than the energy E of the electron.*

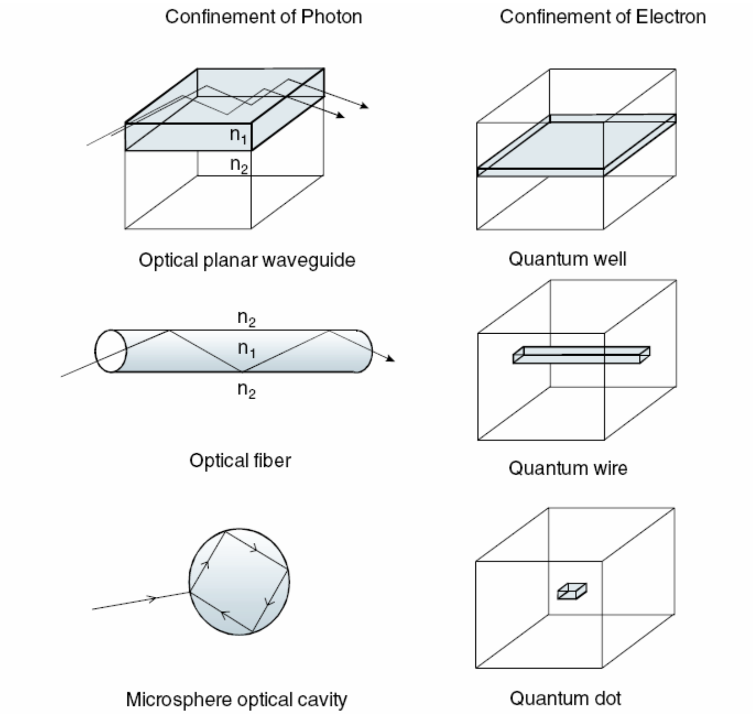


Figure 2.2. Confinements of photons and electrons in various dimensions and the configurations used for them. The propagation direction is z.

$$\mathbf{E} = \tfrac{1}{2} f(x, y) a(z)(e^{i\beta z} + e^{-i\beta z}) \qquad \Psi_n(x) = \frac{1}{2i}\left(\frac{2}{l}\right)^{1/2}(e^{ikx} - e^{-ikx})$$

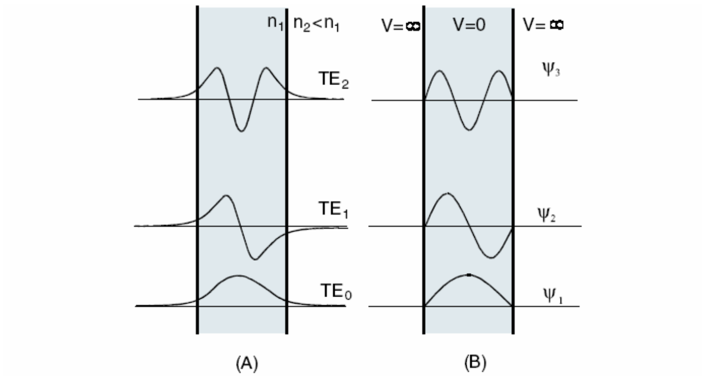


Figure 2.3. (A) Electric field distribution for TE modes $n = 0, 1, 2$ in a planar waveguide with one-dimensional confinement of photons. (B) Wavefunction ψ for quantum levels $n = 1, 2, 3$ for an electron in a one-dimensional box.

Propagation Through a Classically Forbidden Zone: Tunneling

In a classical picture, the photons and electrons are completely confined in the regions of confinement.
For photons, it is seen by the ray optics for the propagating wave as shown in Figure 2.2.
Similarly, classical physics predicts that, once trapped within the potential energy barriers where the energy *E of an electron is less than* the potential energy *V due to the barrier, the electron will remain completely confined* within the walls.

However, the wave picture does not predict so.
The field distribution of light confined in a waveguide extends beyond the boundaries of the waveguide.

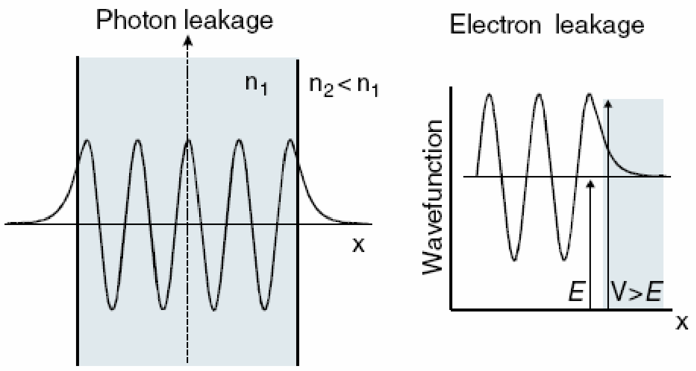


Figure 2.5. Schematic representation of leakage of photons and electrons into classically energetically forbidden regions.

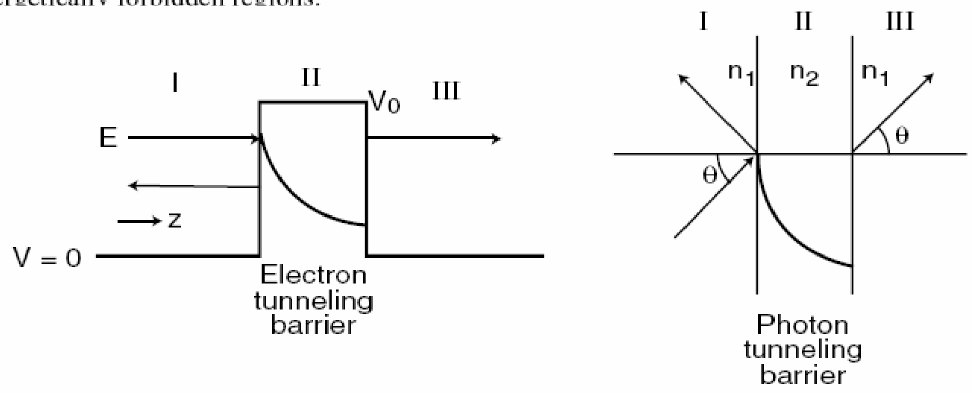


Figure 2.6. Schematics of electron and photon tunneling through a barrier.

This light leakage generates an electromagnetic field called evanescent wave.

$$\mathbf{E}_x = \mathbf{E}_0 \exp(-x/d_p)$$

In an analogous fashion, an electron shows a leakage through regions where $E < V$.
The wavefunction extending beyond the box into the region of $V > E$ decays exponentially, just like the evanescent wave for confined light.
The transmission probability is

$$T = ae^{-2kl} \quad k \text{ is equal to } (2mE)^{1/2}/\hbar.$$

Localization Under a Periodic Potential: Bandgap

Both photons and electrons show an analogous behavior when subjected to a periodic potential.

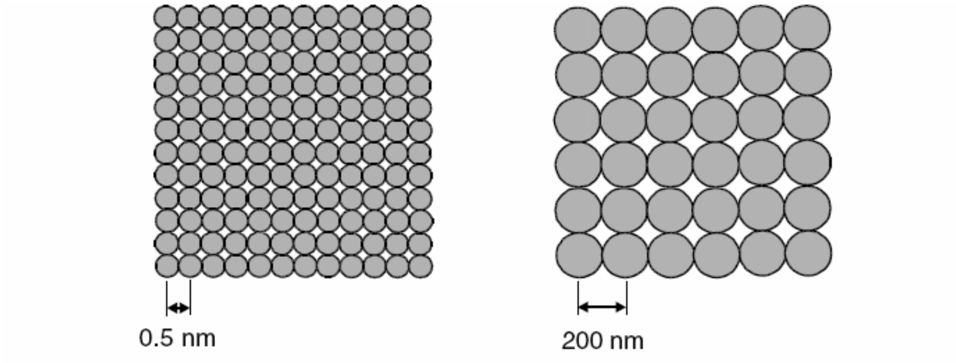


Figure 2.7. Schematic representation of an electronic crystal (*left*) and a photonic crystal (*right*).

The solution of the Schrödinger equation for the energy of electrons, now subjected to the periodic potential *V, produces a splitting of the electronic band:* the lower energy band is called the *valence band, the higher energy band is called the conduction band.* These two bands are separated by a “forbidden” energy gap, the width of which is called the *bandgap.*

In the case of a photonic crystal, the eigenvalue equation for photons can be used to calculate the dispersion relation ω versus *k.* A similar type of band splitting is observed for a photonic crystal, and a forbidden frequency region exists between the two bands, similar to that between the valence and the conduction band of an electronic crystal, which is often called the photonic bandgap.

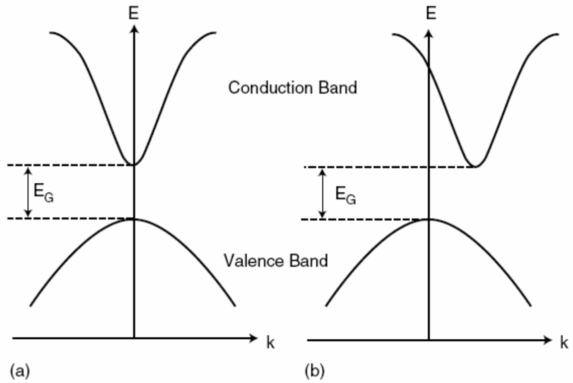


Figure 2.8. Schematics of electron energy in (a) direct bandgap (e.g., GaAs, InP, CdS) and (b) indirect bandgap (e.g., Si, Ge, GaP) semiconductors.

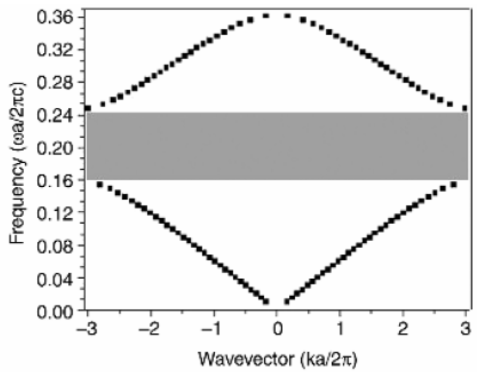
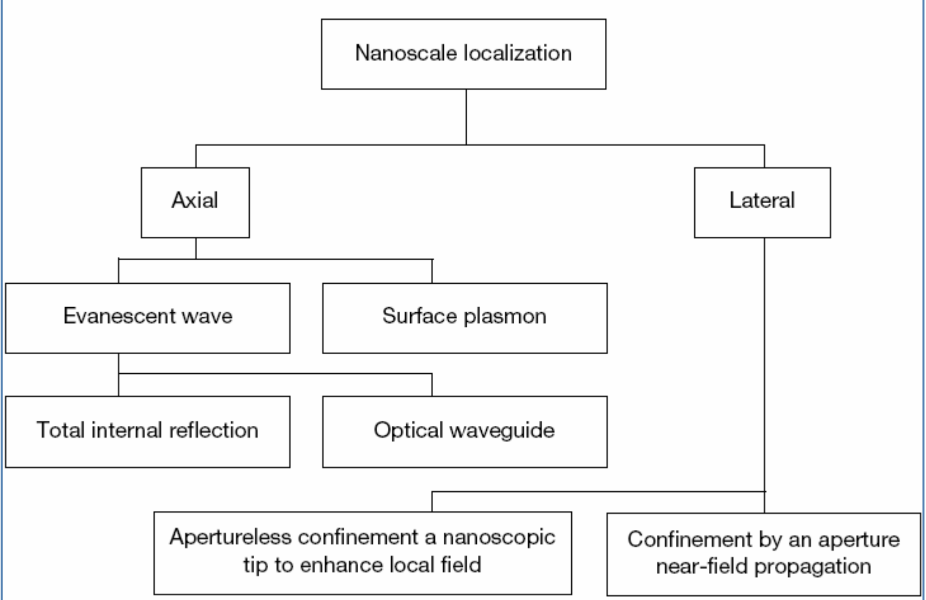


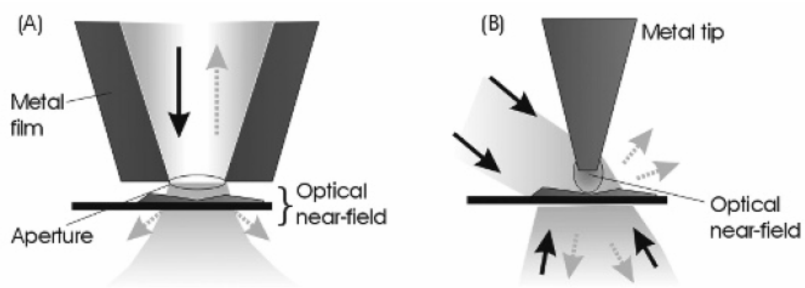
Figure 2.9. Dispersion curve for a one-dimensional photonic crystal showing the lowest energy bandgap.

NANOSCALE OPTICAL INTERACTIONS

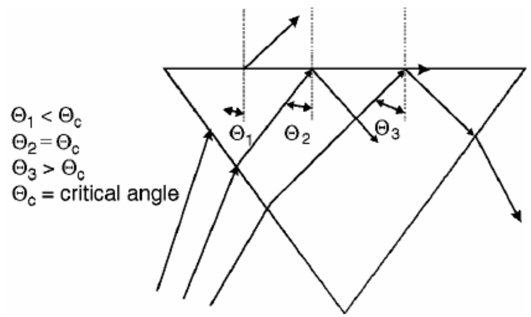
Table 2.2. Methods for Nanoscale Localization of Electromagnetic Field



Lateral Nanoscopic Localization – NSOM, SNOM



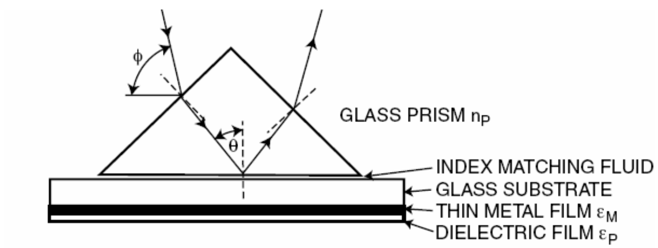
Axial Nanoscopic Localization - *Evanescent Wave*



The penetration depths d_p for the visible light are 50–100 nm.

$$d_p = \lambda/[4\pi n_1\{\sin^2\theta - (n_2/n_1)^2\}^{1/2}]$$

Axial Nanoscopic Localization - *Surface Plasmon Resonance*



$$k_{sp} = (\omega/c)\ [(\varepsilon_m\varepsilon_d)/(\varepsilon_m + \varepsilon_d)]^{1/2}$$

NANOSCALE CONFINEMENT OF ELECTRONIC INTERACTIONS

Table 2.3. Various Nanoscale Electronic Interactions Producing Important Consequences in the Optical Properties of Materials

- **Nanoscale Electronic Interactions**
  - **Quantum confinement effects**
    Confinement of electronic motion (localization) to produce new optical transitions and modified optical interactions
  - **Nanoscopic Interactions to control dynamics**
    Control of local interactions and phonon density of states to manipulate radiative and nonradiative transitions
  - **New cooperative optical transitions**
    - **New cooperative absorption**
      Two or more neighboring atoms or molecules within nanometer distances absorbing collectively
    - **Nanoscale electronic energy transfer**
      Exciton transfer and fluorescence resonance energy transfer (FRET)
    - **Cooperative Emission**
      Cooperative emission by an ion pair through a virtual state

Quantum-Confined Materials - INORGANIC SEMICONDUCTORS

Table 4.1. Semiconductor Material Parameters in the bulk phase

Material	Periodic Table Classification	Bandgap Energy (eV)	Bandgap Wavelength (μm)	Exciton Bohr Radius (nm)	Exciton Binding Energy (meV)
CuCl	I–VII	3.395	0.36	0.7	190
CdS	II–VI	2.583	0.48	2.8	29
CdSe	II–VI	1.89	0.67	4.9	16
GaN	III–V	3.42	0.36	2.8	
GaP	III–V	2.26	0.55	10–6.5	13–20
InP	III–V	1.35	0.92	11.3	5.1
GaAs	III–V	1.42	0.87	12.5	5
AlAs	III–V	2.16	0.57	4.2	17
Si	IV	1.11	1.15	4.3	15
Ge	IV	0.66	1.88	25	3.6
$Si_{1-x}Ge_x$	IV	$1.15-0.874x + 0.376x^2$	$1.08-1.42x + 3.3x^2$	$0.85-0.54x + 0.6x^2$	$14.5-22x + 20x^2$
PbS	IV–VI	0.41	3	18	4.7
AlN	III–V	6.026	0.2	1.96	80

The bandgap can also be tuned by varying the composition of a ternary semiconductor such as $Al_xGa_{1-x}As$, *which for* $x = 0.3$ *has a bandgap of 1.89 eV compared* with 1.42 eV for pure GaAs.

Quantum-Confined Materials – Density of States

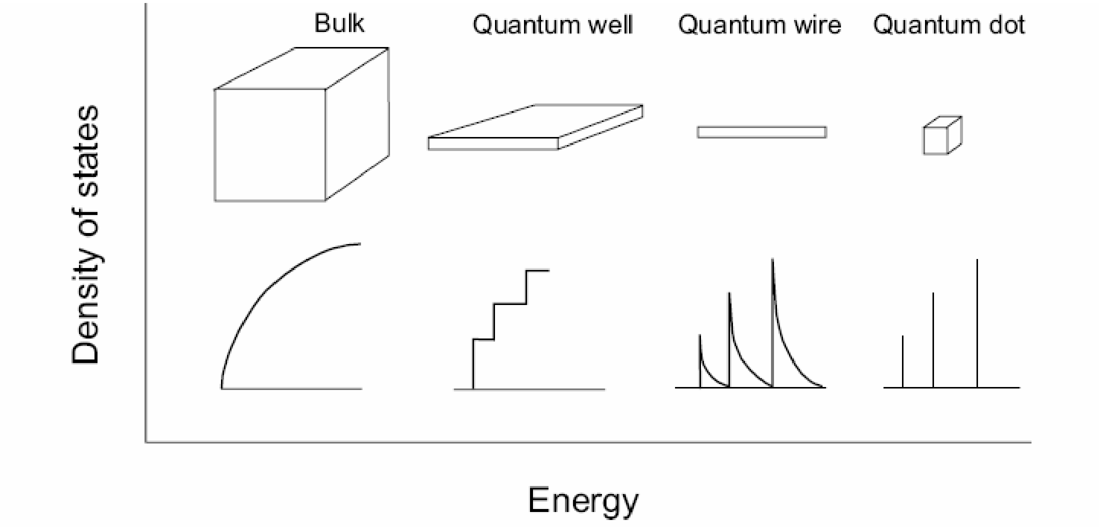


Figure 4.3. Density of states for electrons in bulk conduction band together with those in various confined geometries.

well

$$E_{n,k_x,k_y} = E_C + \frac{n^2h^2}{8m_e^* l^2} + \frac{\hbar^2(k_x^2 + k_y^2)}{2m_e^*}$$

$$D(E) = m_e^*/\pi^2 \qquad \text{for } E > E_1$$

wire

$$E_{n_1,n_2,k_y} = E_C + \frac{n_1^2h^2}{8m_e^* l_x^2} + \frac{n_2^2h^2}{8m_e^* l_z^2} + \frac{\hbar^2 k_y^2}{2m_e^*}$$

$$D(E) \propto (E - E_{n_1,n_2})^{-1/2}$$

dot

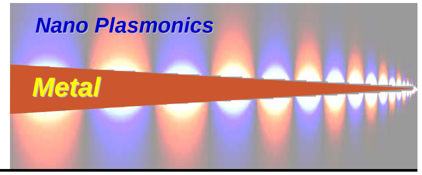
$$E_n = \frac{h^2}{8m_e}\left[\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2\right]$$

$$D(E) \propto \sum_{E_n} \delta(E - E_n)$$

A major factor in the expression for the strength of optical transition (often defined as the oscillator strength) is the density of states.

The density of states *D(E),* defined by the number of energy states between energy *E and E + dE,* is determined by the derivative *dn(E)/dE.*

The density of states in the vicinity of the bandgap is relatively large compared to the case of a bulk semiconductor for which *D(E) vanishes.* Hence, the oscillator strength in the vicinity of the bandgap is considerably enhanced for a quantum well compared to a bulk semiconductor.



MANIFESTATIONS OF QUANTUM CONFINEMENT

Size Dependence of Optical Properties. Quantum confinement produces a blue shift in the bandgap as well as appearance of discrete subbands corresponding to quantization along the direction of confinement.
As the dimensions of confinement increase, the bandgap decreases; hence the interband transitions shift to longer wavelengths, finally approaching the bulk value for a large width.

Increase of Oscillator Strength. Quantum confinement produces a major modification in the density of states both for valence and conduction bands. The oscillator strength of an optical transition for an interband transition depends on the joint density of states of the levels in the valence band and the levels in the conduction bands, between which the optical transition occurs.

New Intraband Transitions. In quantum-confined structures, there are sub-bands characterized by the different quantum numbers (*n = 1, 2, . . .)*These new transitions are in IR and have been utilized to produce inter sub-band detectors and lasers, the most interesting of which are quantum cascade lasers

Increased Exciton Binding. Quantum confinement of electrons and holes also leads to enhanced binding between them and thereby produces increased exciton binding energy. Thus, excitonic resonances are very pronounced in quantum-confined structures and, in the strong confinement conditions, can be seen even at room temperature.

Increase of Transition Probability in Indirect Gap Semiconductor. In the quantum-confined structures, confinement of electrons produces a reduced uncertainty Δx *in its position* and, consequently, produces a larger uncertainty Δk in its quasi-momentum. Confinement, therefore, relaxes the quasi-momentum Δk selection rule, thus allowing enhanced emission to be observed in porous silicon and silicon nanoparticles.

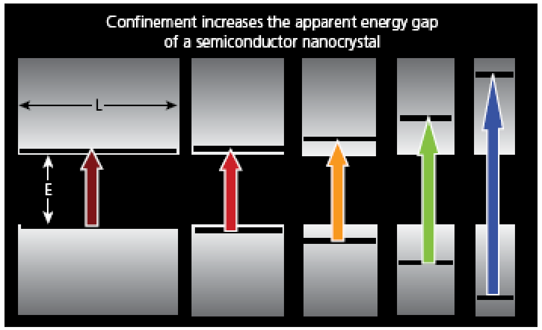


Figure 2. Schematic of the effect of the decreased size of the box on the increased energy gap of a semiconductor quantum dot, and the resultant luminescent color change from bulk materials (left) to small nanocrystals (right).

Table 4.2. Optics of Quantum Confined Semiconductors

Optical Transitions
- Absorption
  - Interband: Transition between modified valence and conduction bands
  - Intraband (Inter-sub-band): Transition between quantized sub-bands of a band (e.g., conduction band)
- Luminescence
  - Photoluminescence: Optically excited emission
  - Electroluminescence: Emission generated by recombination of electrically injected electrons and holes

Nanophotonics for Biotechnology and Nanomedicine

Nano Plasmonics

Metal

Table 13.1. Applications of Various Nanoparticles for Optical Diagnostics and Therapy

Nanoparticles

Optical Diagnostics

Bioimaging

- Quantum dots
- Up-converting nanophosphors
- Encapsulated dyes

Biodetection

- Plasmonic nanostructures
- Silicon microcavities
- Photonic crystal biosensors
- PEBBLES
- Dye-doped nanoparticles
- Nanofiber sensors

Therapy

Optical tracking using nanoclinic

- Magnetic therapy
- Gene therapy

Light-activated therapy

- Light-activated photodynamic therapy using nanoclinic
- Up-conversion photodynamic therapy using two-photon absorbing nanostructures

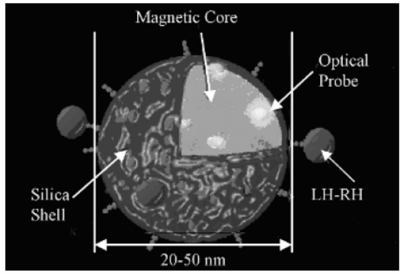
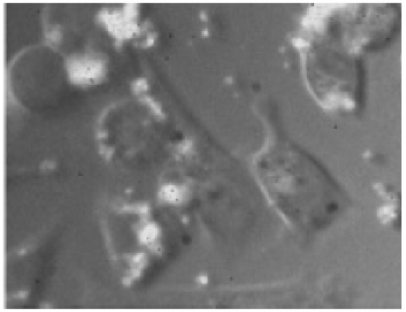
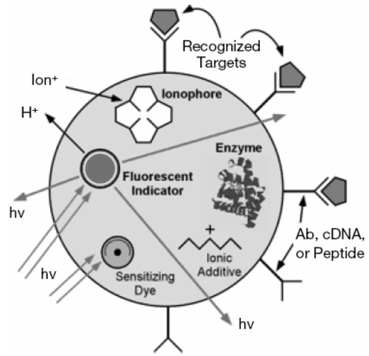
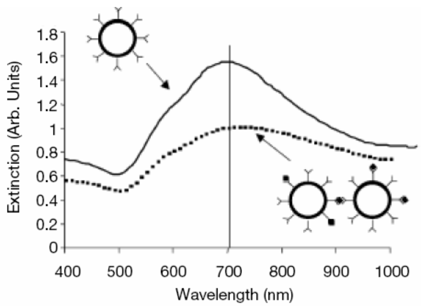


Figure 13.6. Illustrated representation of a nanoclinic.







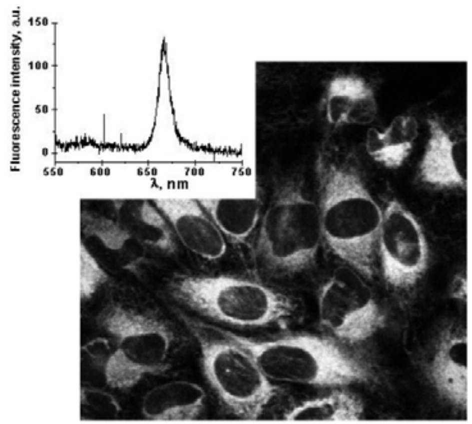


Figure 13.12. Confocal fluorescence image of tumor cells treated with HPPH-doped nanoparticles. (**Inset:**) HPPH fluorescence spectra taken from the cytoplasm of cell.