Semiconductor Fundamentals for Light Emitting Devices

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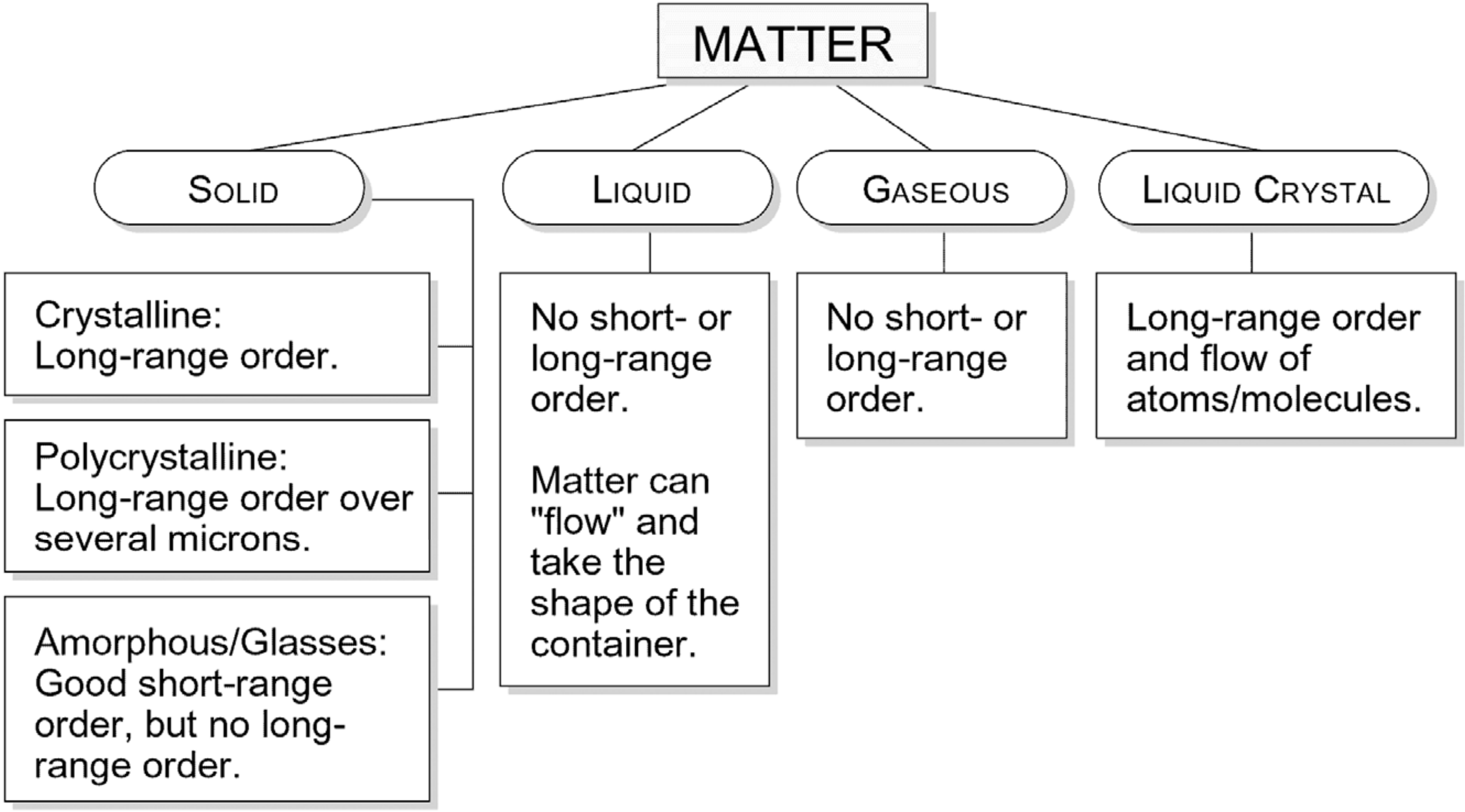
Introduction

Electronic Materials

Electronic materials can be classified into three categories:

METALS	SEMICONDUCTORS	INSULATORS
• Have very low resistivities ($\sim 10^{-6}\ \Omega$cm). • Resistance is difficult to alter or tailor.	Have resistivities that can be altered by up to 10 orders of magnitude by doping or external biases. **or temperature**	Have extremely high resistivities. It is difficult to alter the resistivity through doping or external fields.
⇕ because	⇕ because	⇕ because
Highest occupied energy band is partially filled with electrons.	Highest occupied energy band (valence band) is completely filled with electrons at low temperature. Next band (conduction band) is empty.	High bandgap between valence band (filled) and conduction band (empty) is large ($\gtrsim 4$ eV).

Material States



MATTER

SOLID

LIQUID

GASEOUS

LIQUID CRYSTAL

Crystalline:
Long-range order.

Polycrystalline:
Long-range order over several microns.

Amorphous/Glasses:
Good short-range order, but no long-range order.

No short- or long-range order.

Matter can "flow" and take the shape of the container.

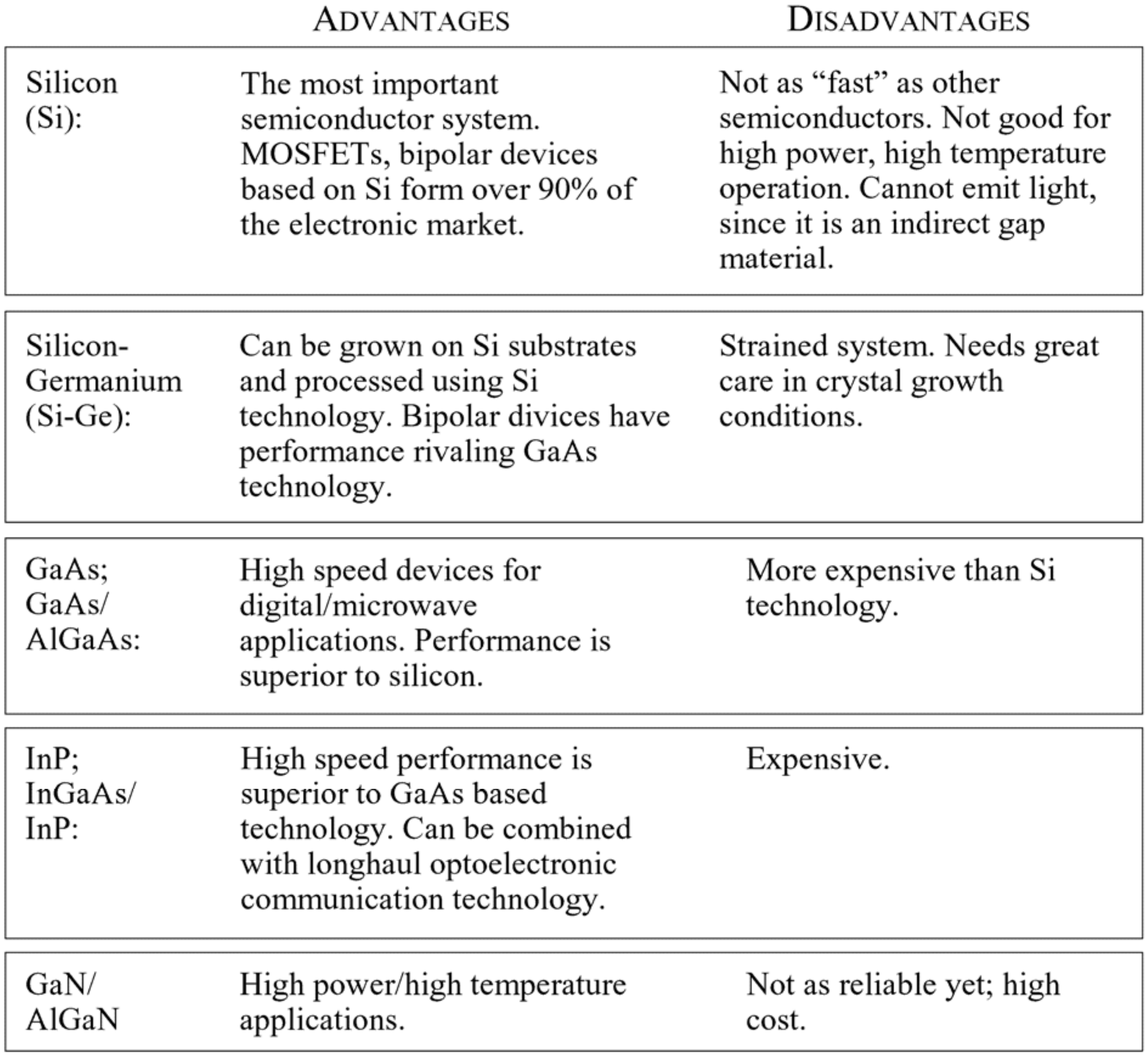
No short- or long-range order.

Long-range order and flow of atoms/molecules.

Why III-V Compound?

- Optoelectronic Devices
  - Light emission (direct bandgap)
    - 850nm, 1310nm, 1550nm wavelength
    - Visible light
  - Light detection
  - High speed optical modulator and switch
- Electronic Devices
  - High Speed switching
  - High power operation
    - GaAs
    - GaN

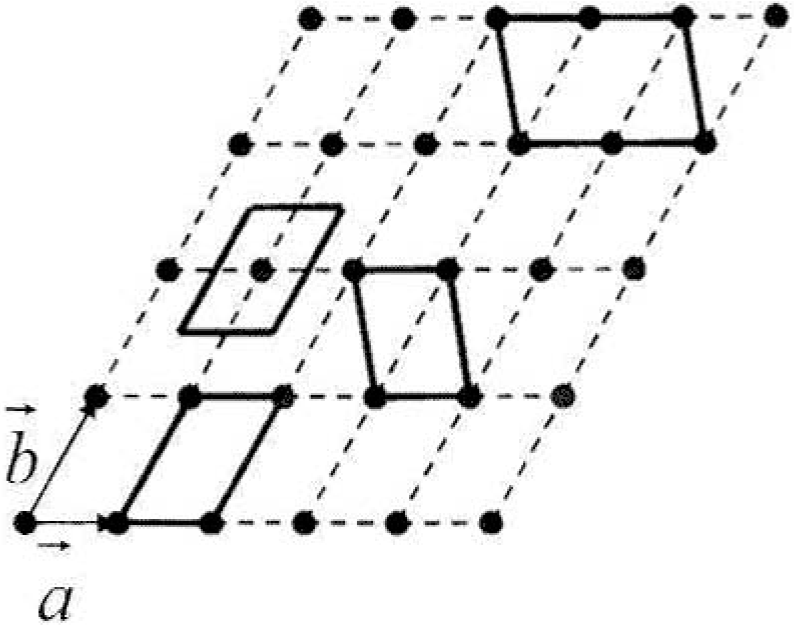
Material Comparison



	ADVANTAGES	DISADVANTAGES
Silicon (Si):	The most important semiconductor system. MOSFETs, bipolar devices based on Si form over 90% of the electronic market.	Not as “fast” as other semiconductors. Not good for high power, high temperature operation. Cannot emit light, since it is an indirect gap material.
Silicon-Germanium (Si-Ge):	Can be grown on Si substrates and processed using Si technology. Bipolar divices have performance rivaling GaAs technology.	Strained system. Needs great care in crystal growth conditions.
GaAs; GaAs/ AlGaAs:	High speed devices for digital/microwave applications. Performance is superior to silicon.	More expensive than Si technology.
InP; InGaAs/ InP:	High speed performance is superior to GaAs based technology. Can be combined with longhaul optoelectronic communication technology.	Expensive.
GaN/ AlGaN	High power/high temperature applications.	Not as reliable yet; high cost.

Crystalline Properties

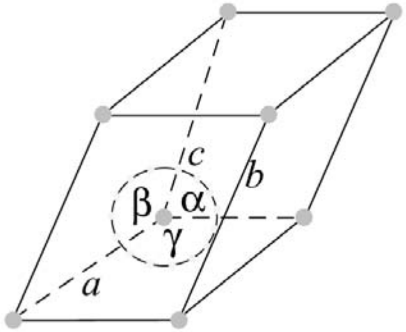
Unit cell, Primitive cell



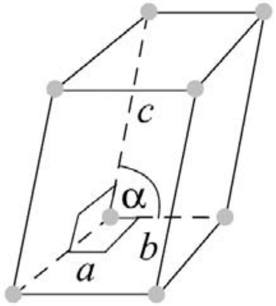
- The unit cell which has the smallest volume is called the primitive cell.
- The choice of a primitive cell is not unique.
- All possible primitive cells have the same volume and contains only one lattice point
- Primitive cell volume = (crystal volume) / (number of primitive cells)

Bravais Lattices

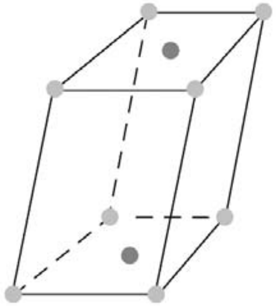
- Bravais proved that only 14 different ways of arranging points in space lattices such that all the lattice points have exactly the same surroundings.
- One point could be a group of atoms



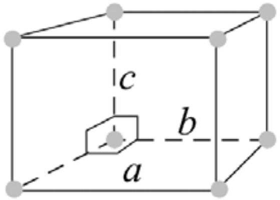
triclinic



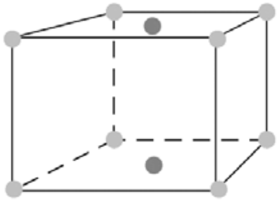
monoclinic



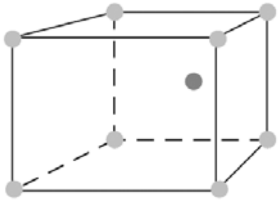
base-centered



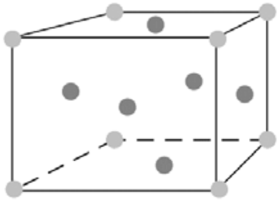
orthorhombic



base-centered

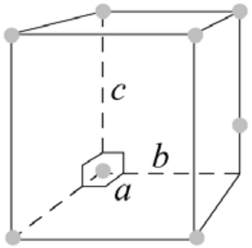


body-centered

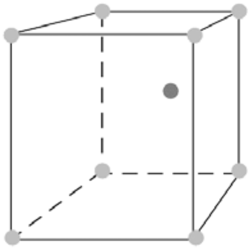


face-centered

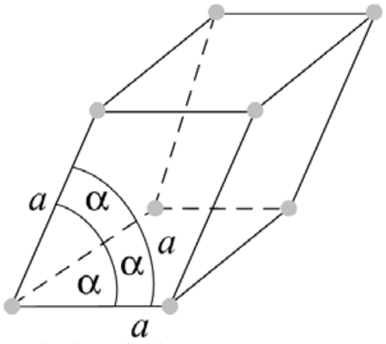
Bravais Lattices (cont’)



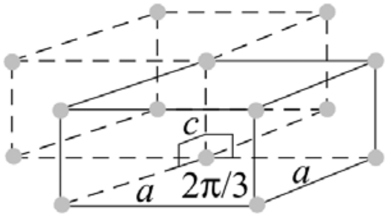
tetragonal



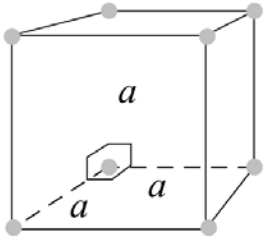
body-centered



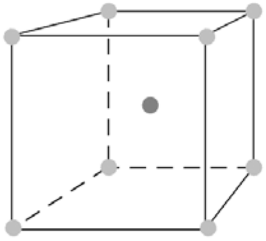
rhomboherdral



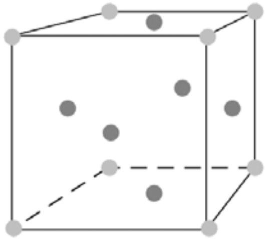
hexagonal



cubic



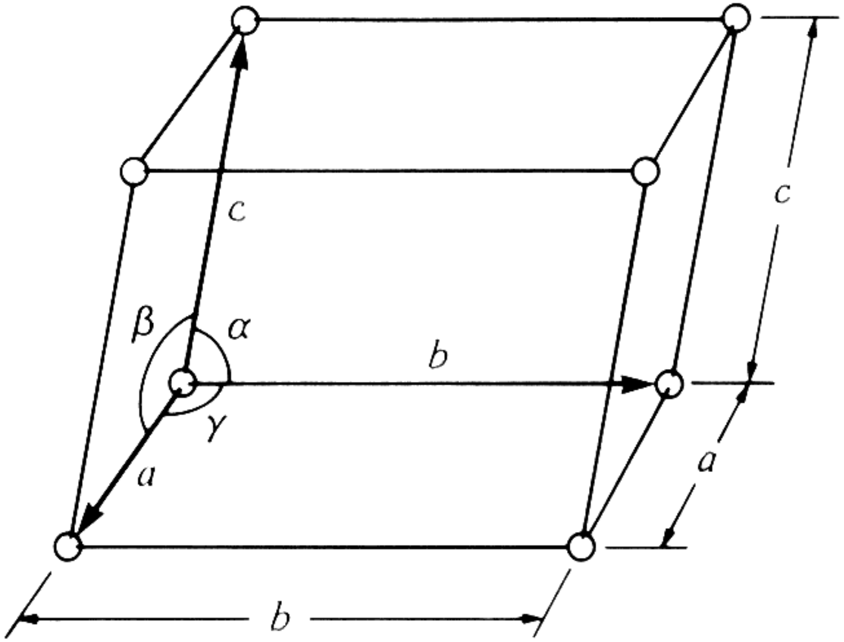
body-cubic



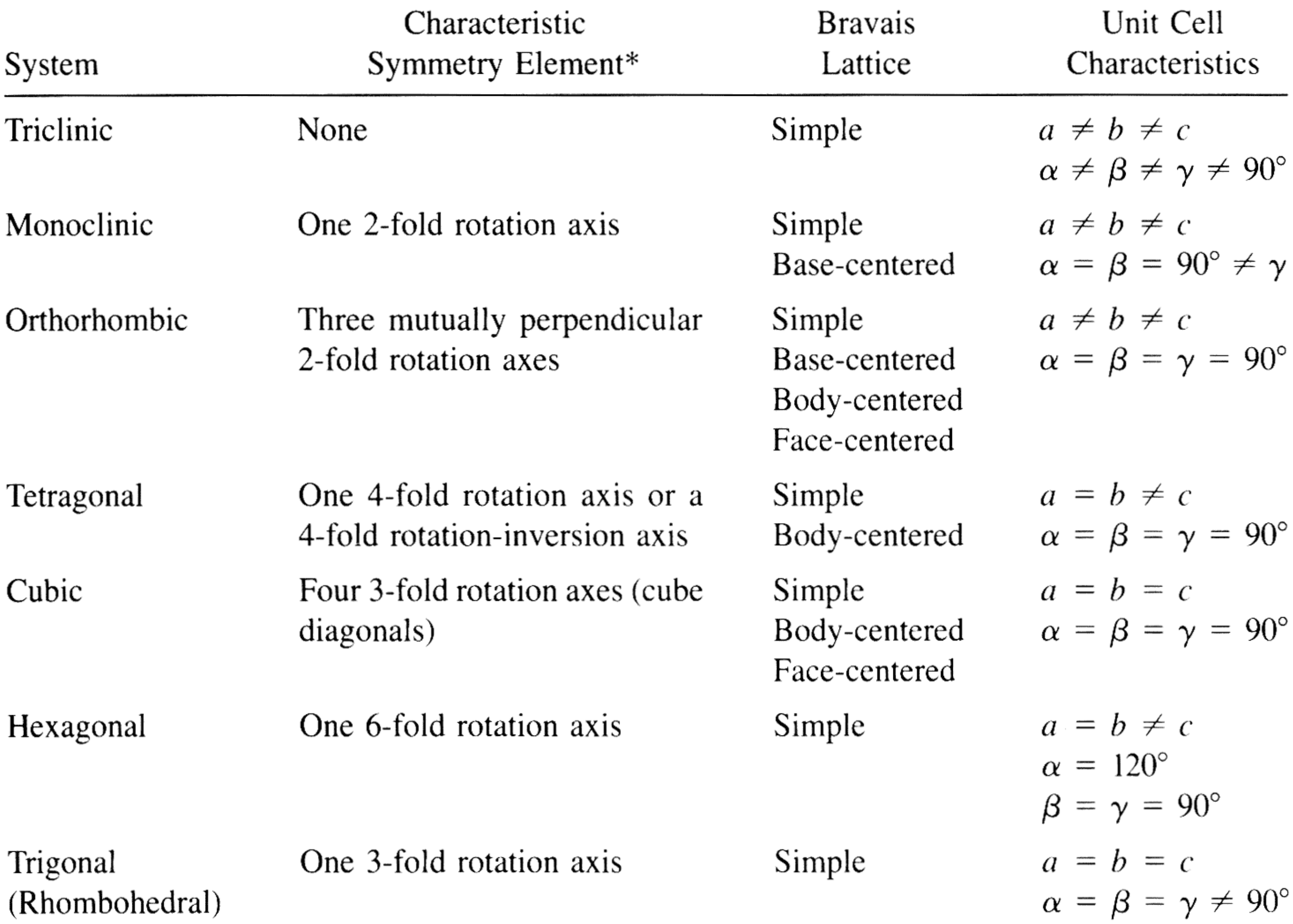
face-centered cubic

Seven Crystal Systems

- N-fold rotation symmetry
- Plane of symmetry
- Inversion center symmetry
- Rotation-inversion symmetry



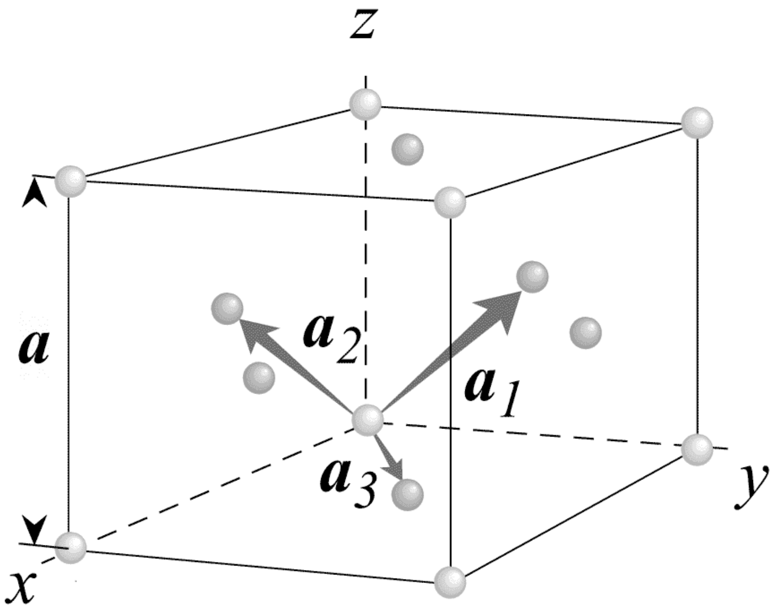
Seven Crystal System



System	Characteristic Symmetry Element*	Bravais Lattice	Unit Cell Characteristics
Triclinic	None	Simple	$a \neq b \neq c$ $\alpha \neq \beta \neq \gamma \neq 90^\circ$
Monoclinic	One 2-fold rotation axis	Simple Base-centered	$a \neq b \neq c$ $\alpha = \beta = 90^\circ \neq \gamma$
Orthorhombic	Three mutually perpendicular 2-fold rotation axes	Simple Base-centered Body-centered Face-centered	$a \neq b \neq c$ $\alpha = \beta = \gamma = 90^\circ$
Tetragonal	One 4-fold rotation axis or a 4-fold rotation-inversion axis	Simple Body-centered	$a = b \neq c$ $\alpha = \beta = \gamma = 90^\circ$
Cubic	Four 3-fold rotation axes (cube diagonals)	Simple Body-centered Face-centered	$a = b = c$ $\alpha = \beta = \gamma = 90^\circ$
Hexagonal	One 6-fold rotation axis	Simple	$a = b \neq c$ $\alpha = 120^\circ$ $\beta = \gamma = 90^\circ$
Trigonal (Rhombohedral)	One 3-fold rotation axis	Simple	$a = b = c$ $\alpha = \beta = \gamma \neq 90^\circ$

Face Centered Cubic

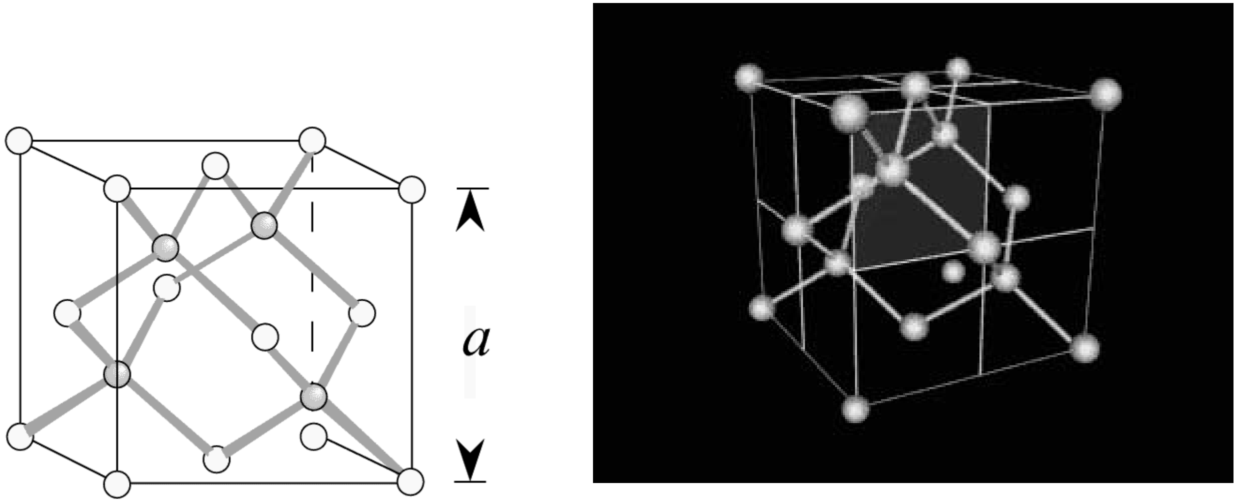
- Most semiconductors have underlying lattice that is either FCC or hexagonal closed pack (hcp)



Primitive basis vectors for the FCC lattice

$$\mathbf{a}_1 = \frac{a}{2}(\mathbf{y}+\mathbf{z}),\ \mathbf{a}_2 = \frac{a}{2}(\mathbf{z}+\mathbf{x}),\ \mathbf{a}_3 = \frac{a}{2}(\mathbf{x}+\mathbf{y})$$

Diamond, Zincblende Lattice

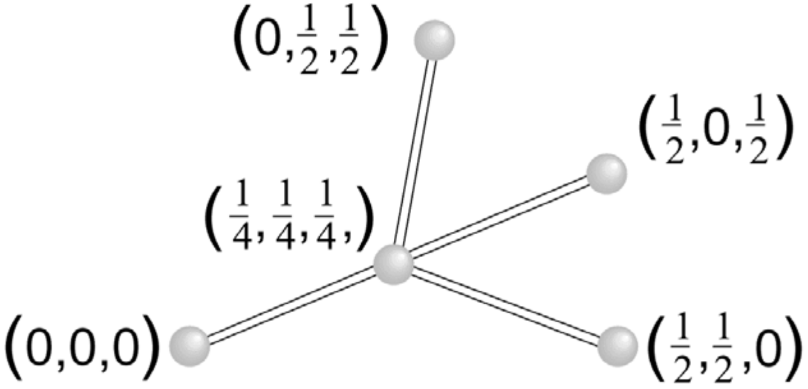


The zinc blende crystal structure. The structure consists of the interpenetrating fcc lattices, one displaced from the other by a distance $\left(\frac{a}{4}\frac{a}{4}\frac{a}{4}\right)$ along the body diagonal. The underlying Bravais lattice is fcc with a two-atom basis. The positions of the two atoms is (000) and $\left(\frac{a}{4}\frac{a}{4}\frac{a}{4}\right)$.

Diamond, Zincblende Lattice

Positions of the atoms

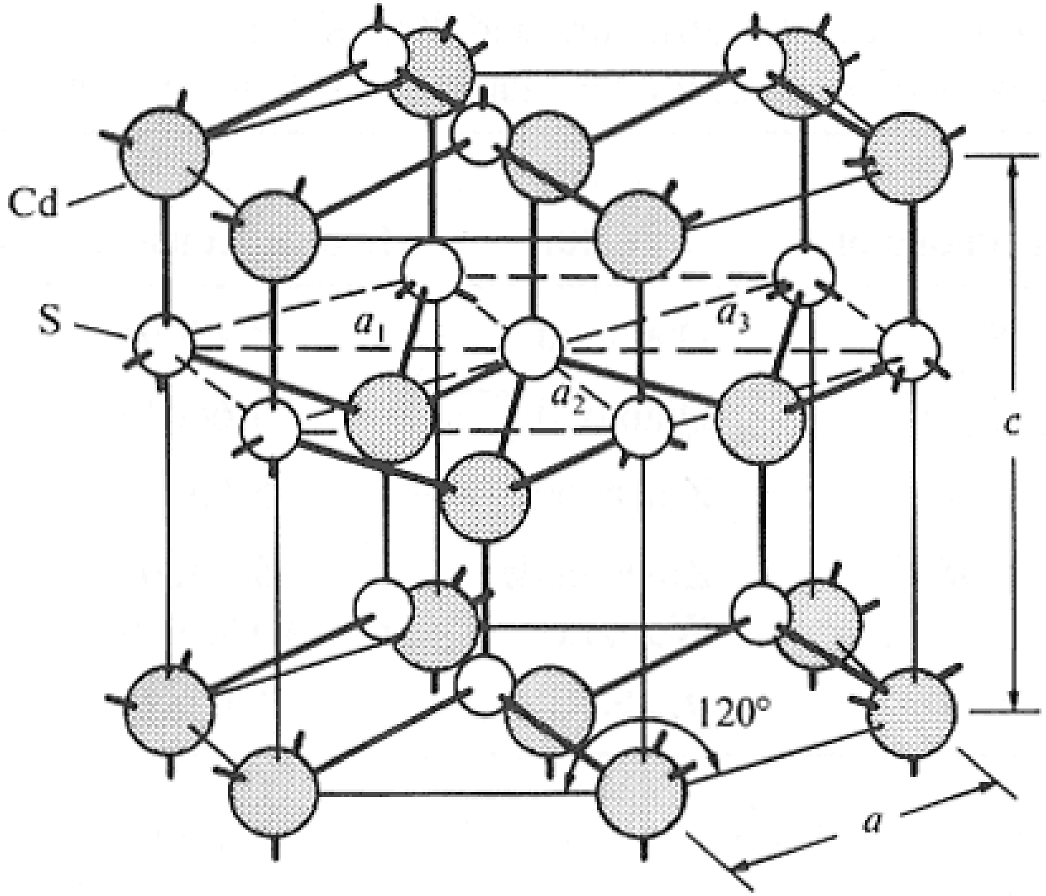
$$
\begin{aligned}
\mathbf{A} = {} & (n_1,n_2,n_3),\ \left(n_1+\tfrac{1}{4},n_2+\tfrac{1}{4},n_3+\tfrac{1}{4}\right), \\
& \left(n_1+\tfrac{1}{2},n_2+\tfrac{1}{2},n_3\right),\left(n_1+\tfrac{3}{4},n_2+\tfrac{3}{4},n_3+\tfrac{1}{4}\right), \\
& \left(n_1+\tfrac{1}{2},n_2,n_3+\tfrac{1}{2}\right),\left(n_1+\tfrac{3}{4},n_2+\tfrac{1}{4},n_3+\tfrac{3}{4}\right), \\
& \left(n_1,n_2+\tfrac{1}{2},n_3+\tfrac{1}{2}\right),\left(n_1+\tfrac{1}{4},n_2+\tfrac{3}{4},n_3+\tfrac{3}{4}\right)
\end{aligned}
$$



Tetrahedral bonding

Nature of chemical bonds in a diamond or zinc blende structure

Wurtzite Lattice (HCP)



FCC & Wurtzite

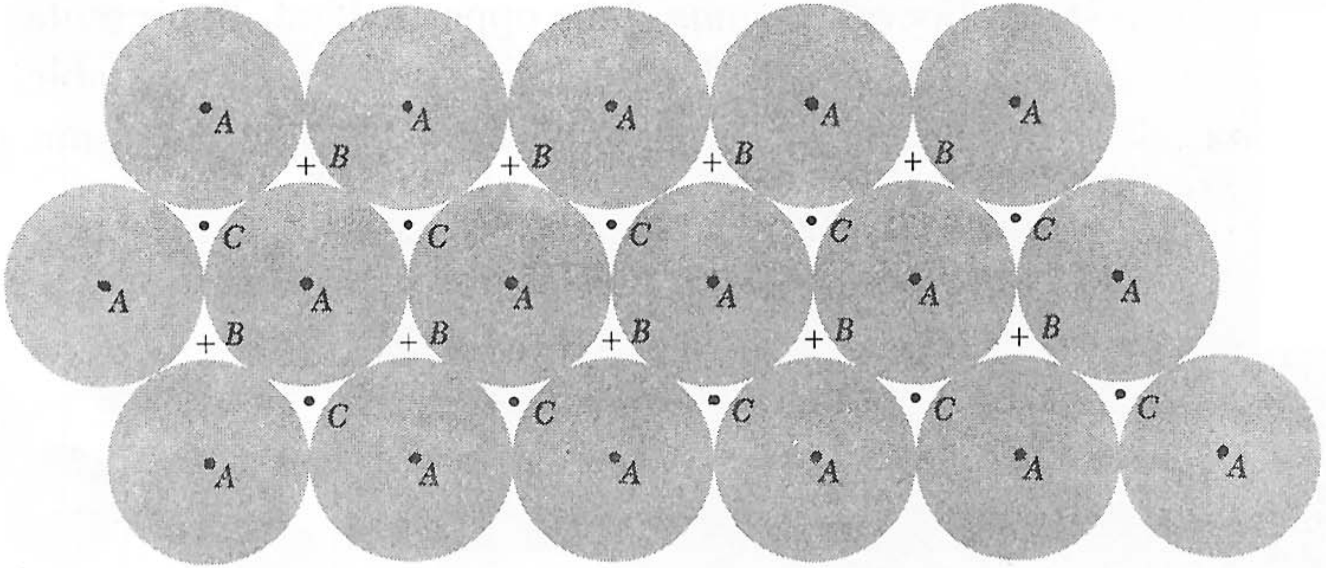
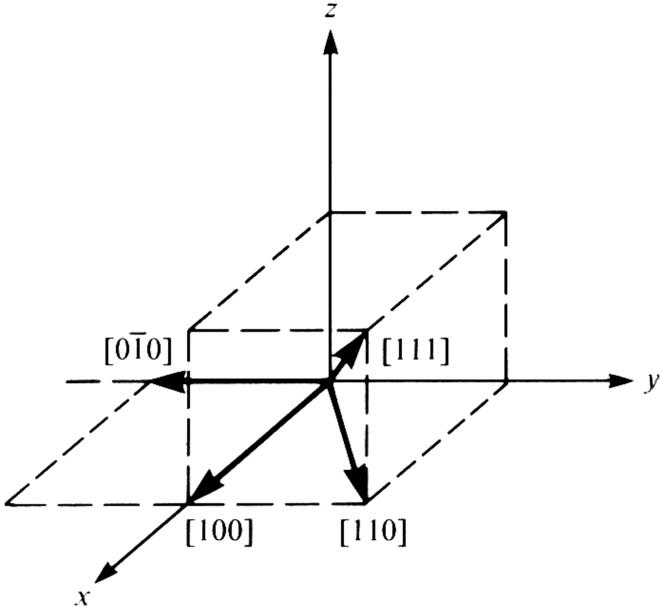


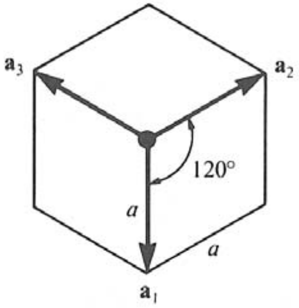
Figure 21 A close-packed layer of spheres is shown, with centers at points marked *A*. A second and identical layer of spheres can be placed on top of this, above and parallel to the plane of the drawing, with centers over the points marked *B*. There are two choices for a third layer. It can go in over *A* or over *C*. If it goes in over *A* the sequence is *ABABAB*. . . and the structure is hexagonal close-packed. If the third layer goes in over *C* the sequence is *ABCABCABC*. . . and the structure is face-centered cubic.

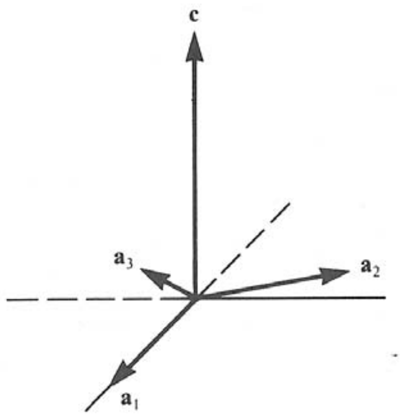
Miller Indices



Convention	Interpretation	
(hkl)	Crystal plane	
$\{hkl\}$	Equivalent planes	
$[hkl]$	Crystal direction	
$\langle hkl\rangle$	Equivalent directions	
$(hkil)$	Plane	Hexagonal system
$[hkil]$	Direction	

$h + k + i = 0$





- Miller indices is essential in dealing with semiconductor materials and device structures.

Example (cubic)

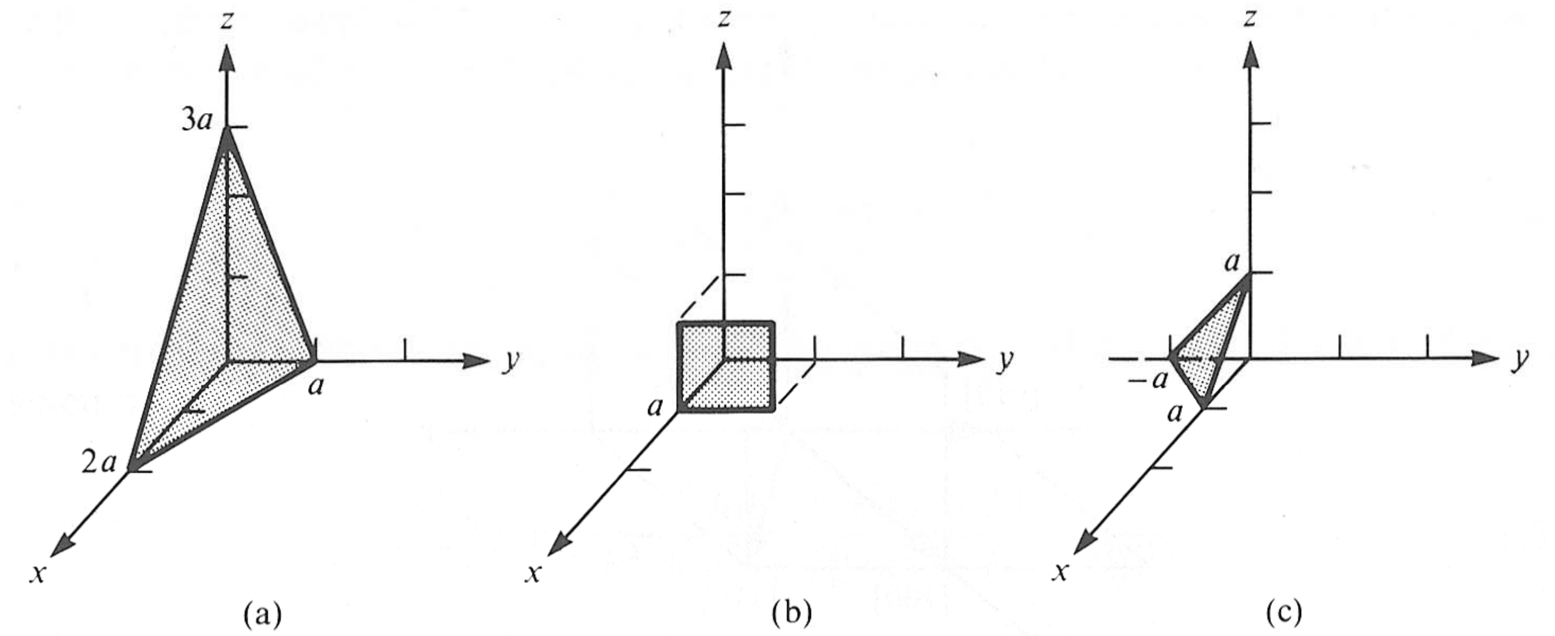
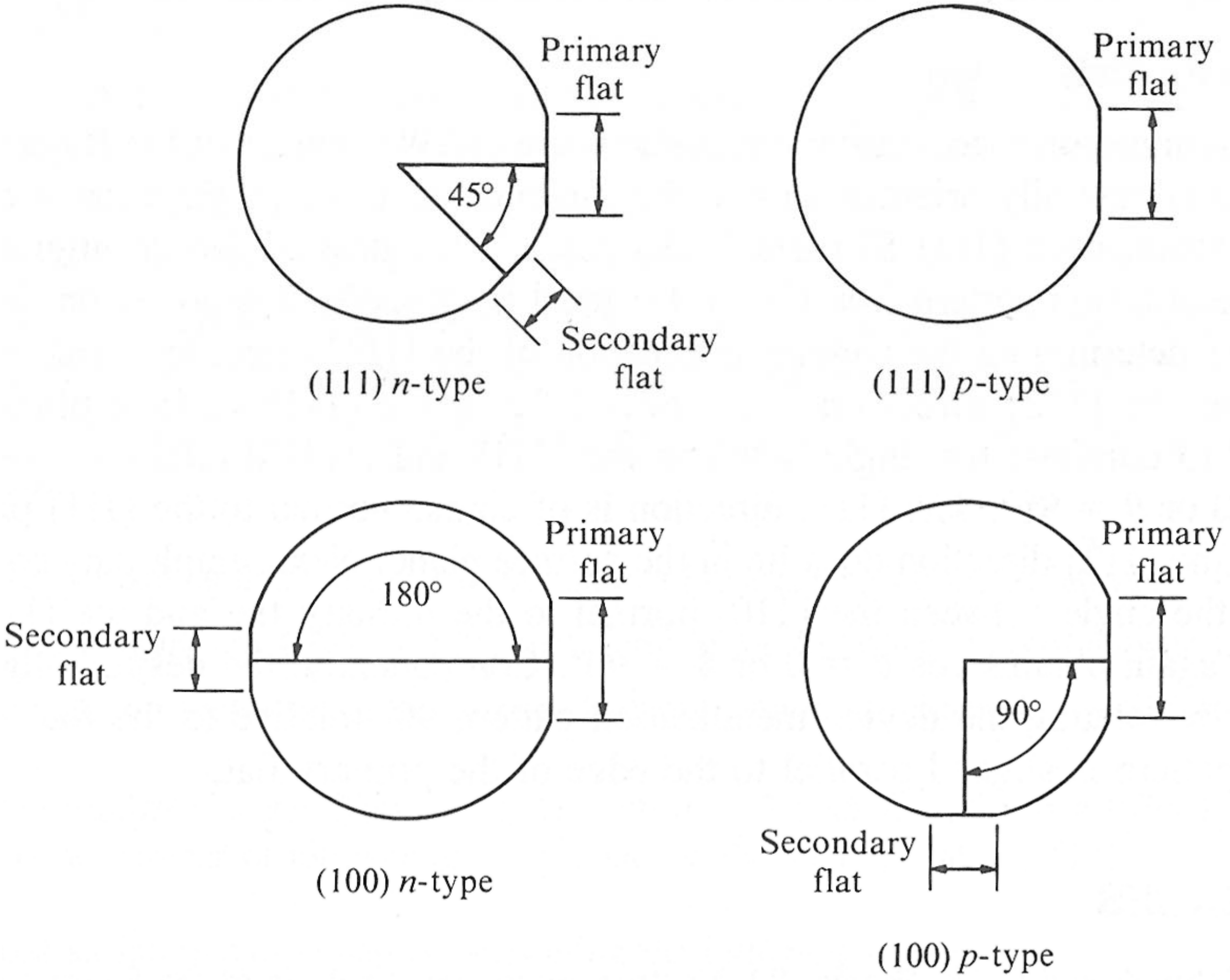


Fig. 1.7 Sample cubic crystal planes. (a) The (362) plane used in explaining the Miller indexing procedure. (b) The (100) plane. (c) The $(1\bar{1}1)$ plane.

For cubic crystals, a plane and the direction normal to the plane have precisely the same indices

Wafer Flats (Si)



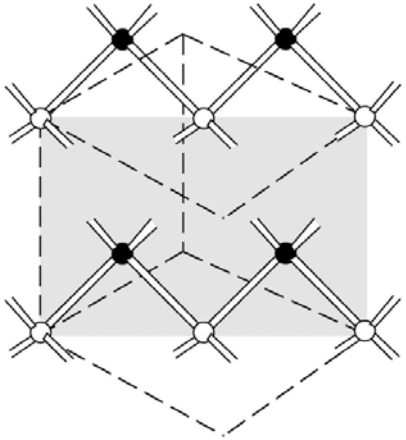
(111) *n*-type

(111) *p*-type

(100) *n*-type

(100) *p*-type

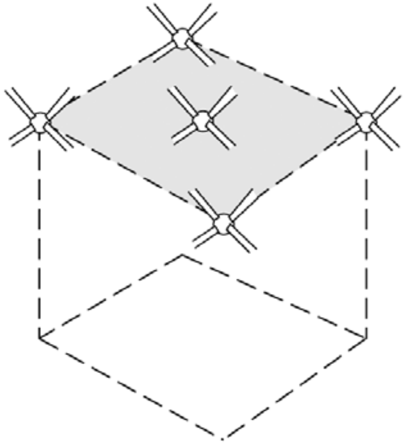
Important Planes in Zincblende or Diamond Structures



ATOMS ON THE (110) PLANE

Each atom has 4 bonds:
- 2 bonds in the (110) plane
- 1 bond connects each atom to adjacent (110) planes

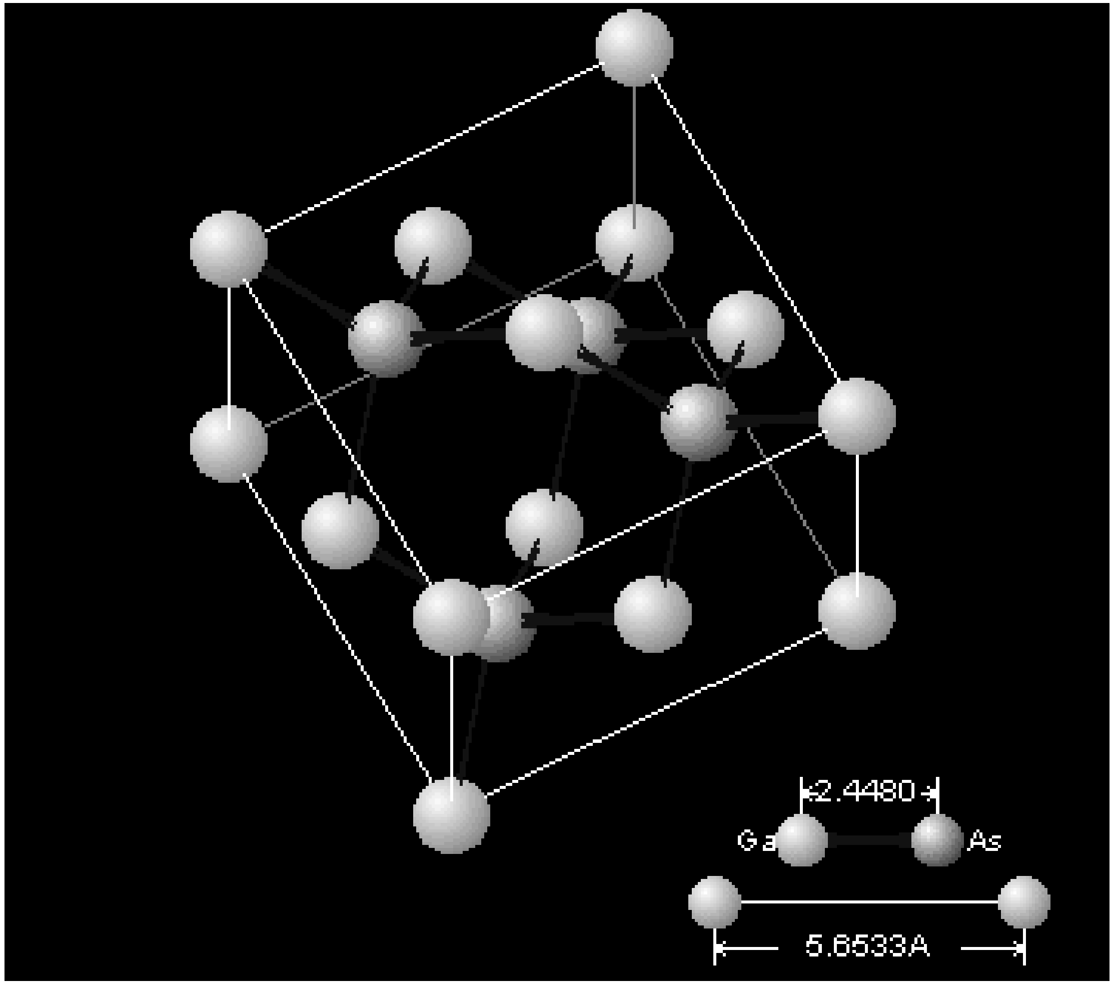
⟹ Cleaving adjacent planes requires breaking 1 bond per atom.



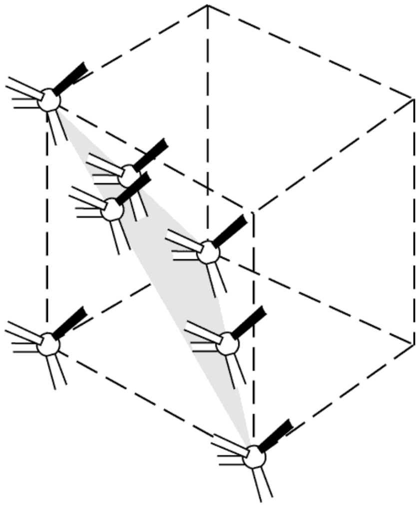
ATOMS ON THE (001) PLANE

2 bonds connect each atom to adjacent (001) plane.
Atoms are either Ga or As in a GaAs crystal.
⟹ Cleaving adjacent planes requires breaking 2 bonds per atom.

(110) Plane



Important Planes in Zinc Blend or Diamond Structures

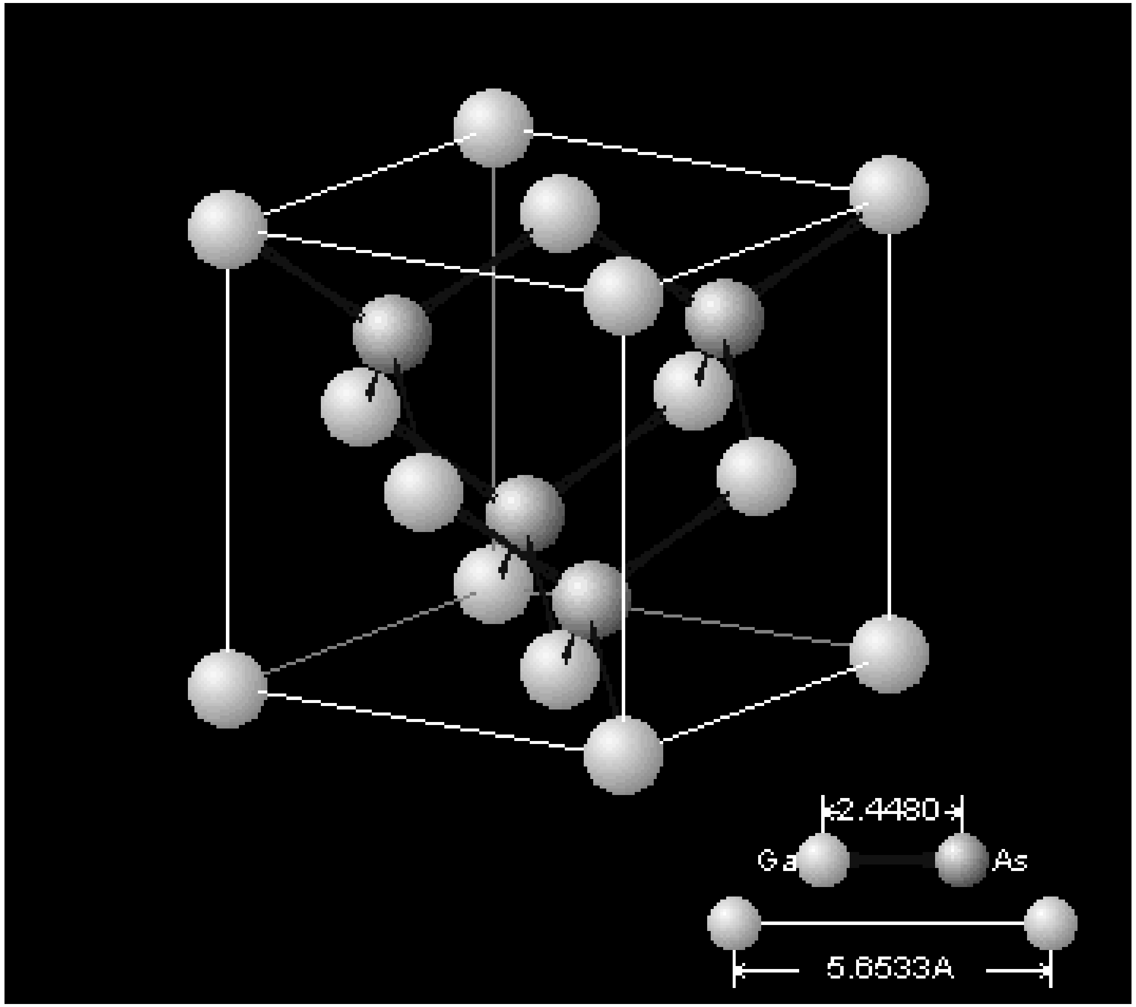


ATOMS ON THE (111) PLANE

Could be either Ga or As.
1 bond connecting an adjacent plane on one side.
3 bonds connecting an adjacent plane on the other side.

- This figures also show how many bond connect adjacent planes. This number determines how easy or difficulty it is to cleave the crystal along the these plans by cutting the bonds joining the adjacent plans

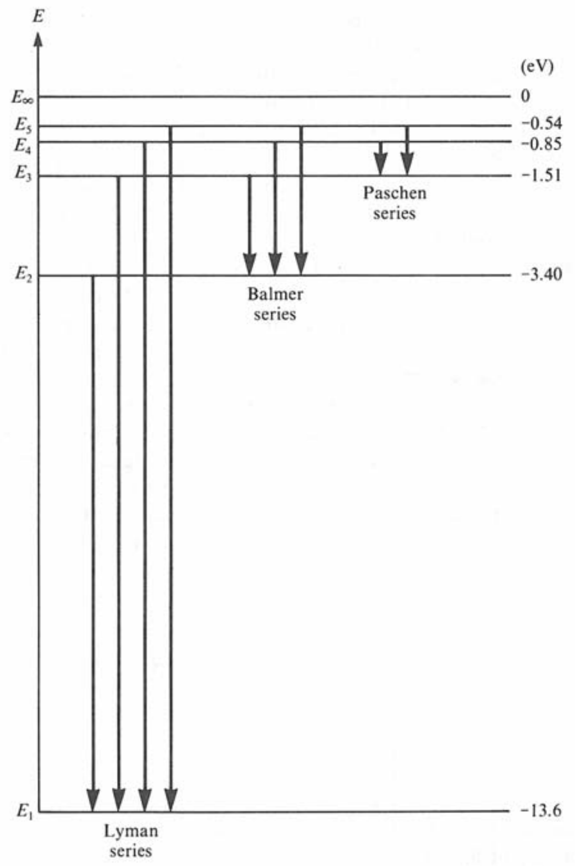
(111) Plane



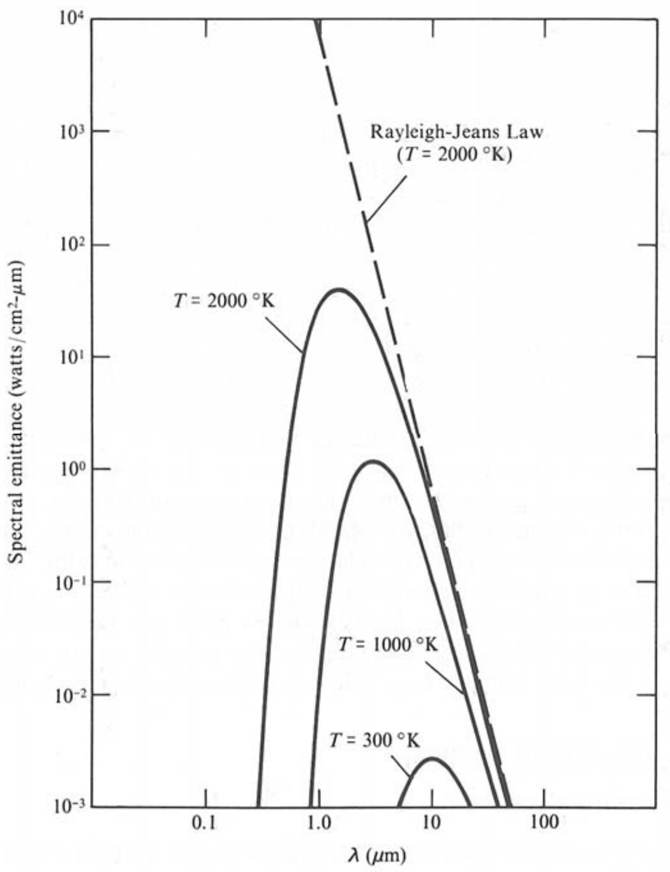
Band Theory

Observations of Quantization

- Black body radiation
  - $E = n \hbar \omega$
- Bohr model for Hydrogen atom
  - $E = -13.6/ n^2$



- Wave-Particle Duality
  - Photoelectric effect
  - ($h\upsilon = \Phi + K_{\max}$)
  - Compton effect



Schrödinger Equation

- Wave mechanics
- An empirical relationship
- Must satisfy 5 basic postulates
- No derivation at all, just like Newton’s law

$$-\frac{\hbar^2}{2m}\nabla^2\Psi + U(x, y, z)\Psi = -\frac{\hbar}{i}\frac{\partial\Psi}{\partial t}$$

Schrödinger Equation

To examine electrons inside a solid we need to use quantum mechanics, i.e., the Schrödinger equation

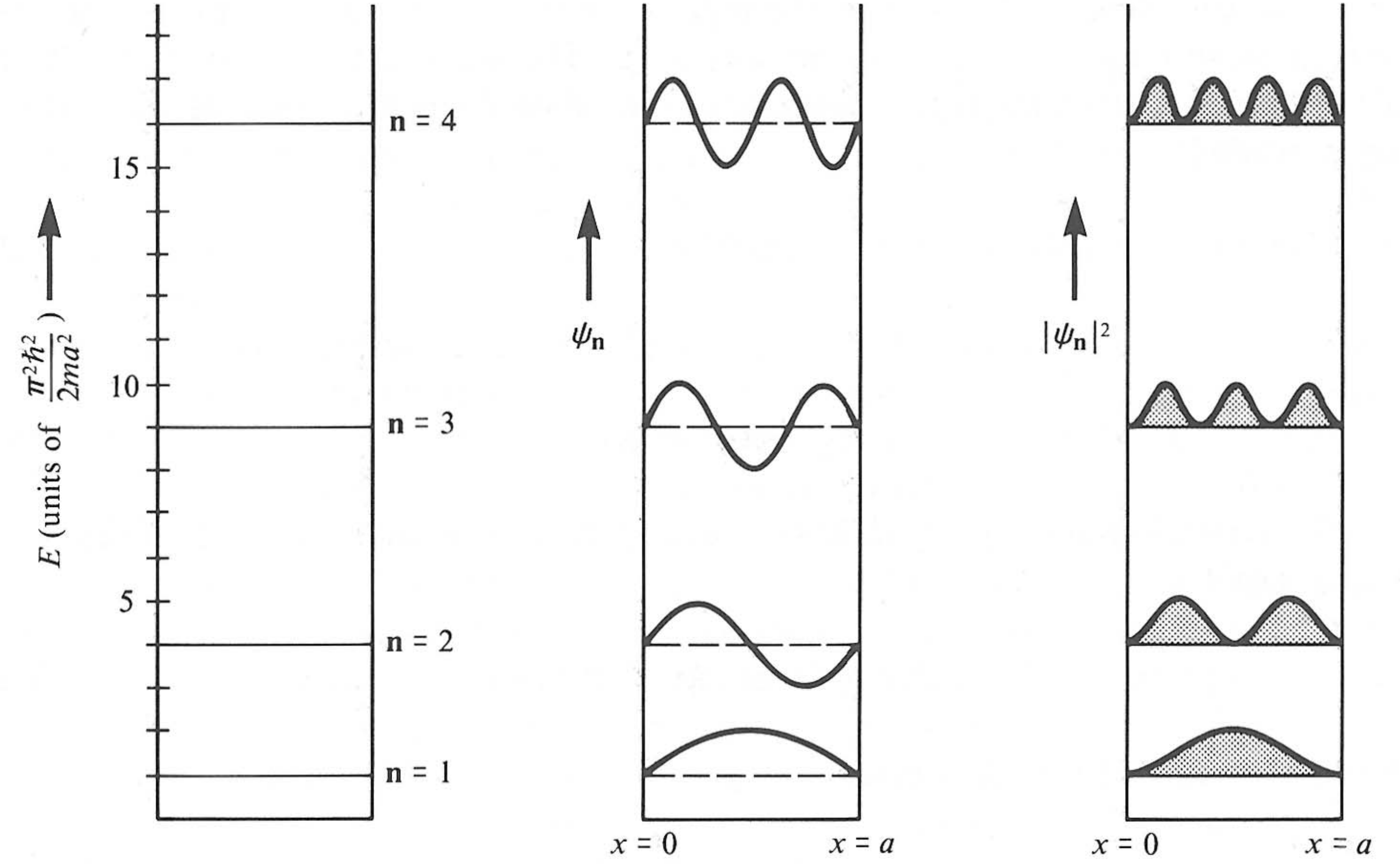
$$\left[\frac{-\hbar^2}{2m_o}\nabla^2 + V(\mathbf{r})\right]\psi(\mathbf{r}) = E\,\psi(\mathbf{r})$$

$\psi(\mathbf{r})$: electronic state or wavefunction.
E : electronic allowed energy or eigenvalue.
$V(\mathbf{r})$: background potential which is periodic in crystals.

Five Postulates

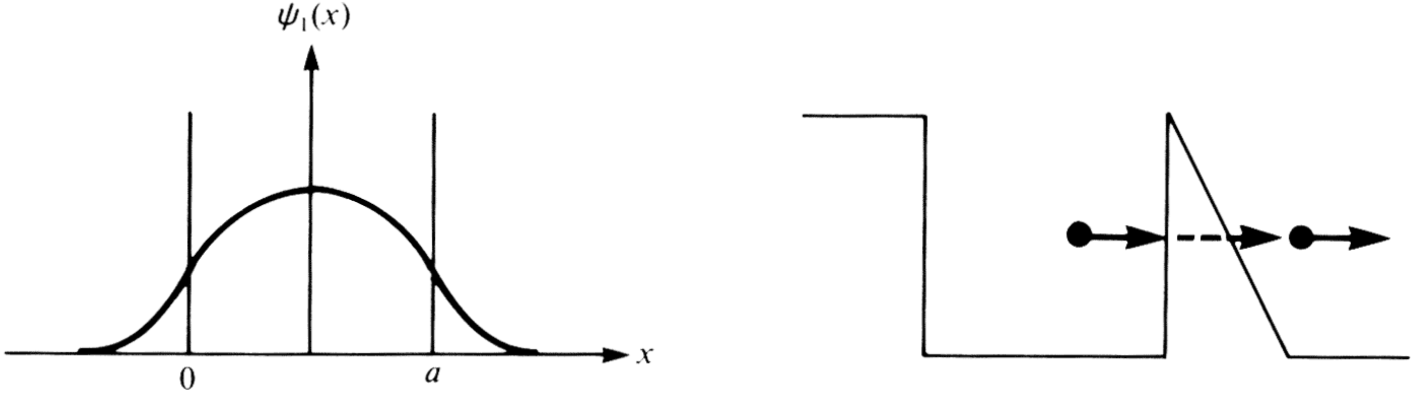
- There exists a wavefunction Ψ (x,y,z,t) which describes the dynamic behavior of the system and all system variables.
- Ψ can be determined by solving the time-dependent Schrodinger equation.
- Ψ and ∇Ψ must be finite, continuous and single-valued for all x, y, z, t
- $\int_{\mathcal{V}} \Psi^* \Psi \, d\mathcal{V} = 1$
- $\langle \alpha \rangle = \int_{\mathcal{V}} \Psi^* \alpha_{op} \Psi \, d\mathcal{V}$

1D Infinite Well Solution



Tunneling

You will understand the tunneling effect by solving a particle confined inside a finite potential barrier

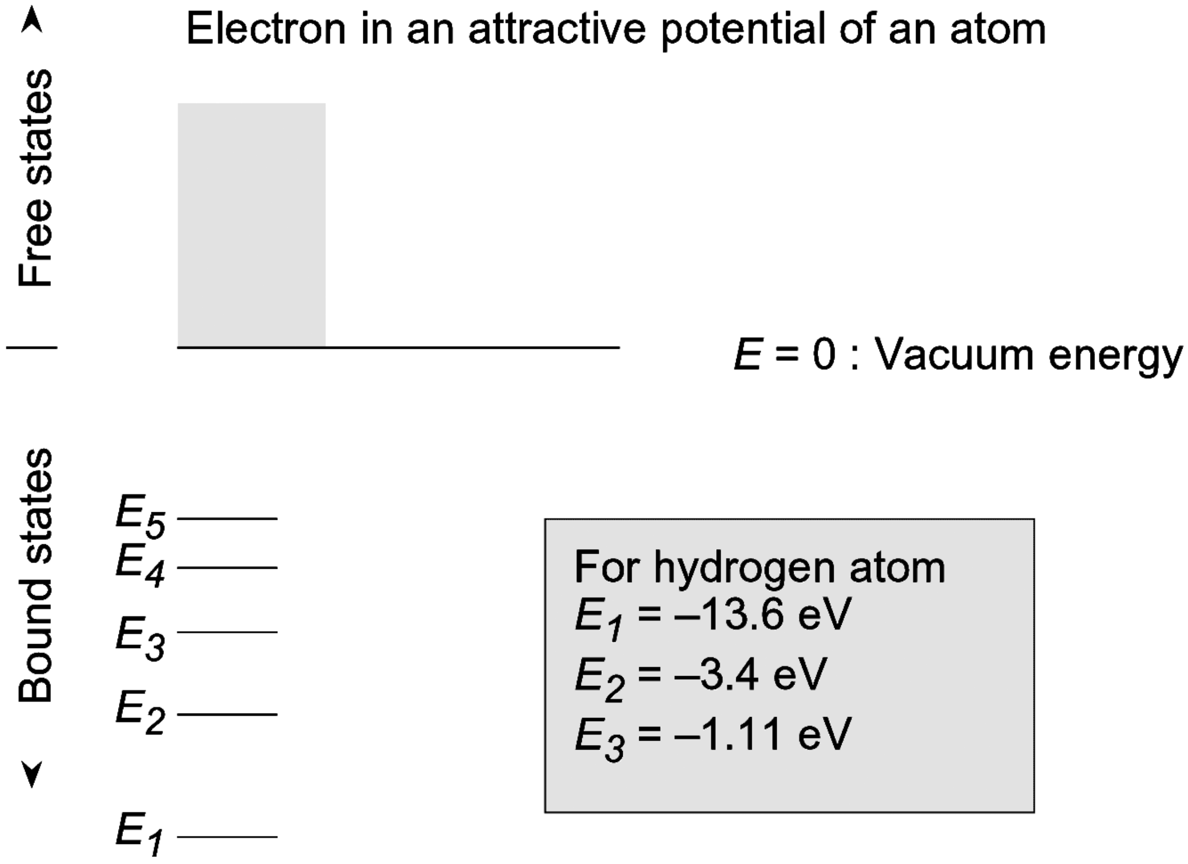


(a) (b)

Fig. 2.9 (a) Sketch of the wavefunction associated with the lowest energy state of a particle in a finite potential well. The sketch emphasizes the finite value of the wavefunction external to the well. (b) Visualization of tunneling through a thin barrier.

Electrons in an Atom

- Before examining electrons in a solid, let us examine electronic states in an atom. Let us first examine a hydrogen atom.



Electron in an attractive potential of an atom

For hydrogen atom

$E_1 = -13.6$ eV

$E_2 = -3.4$ eV

$E_3 = -1.11$ eV

Electrons in Two Atoms

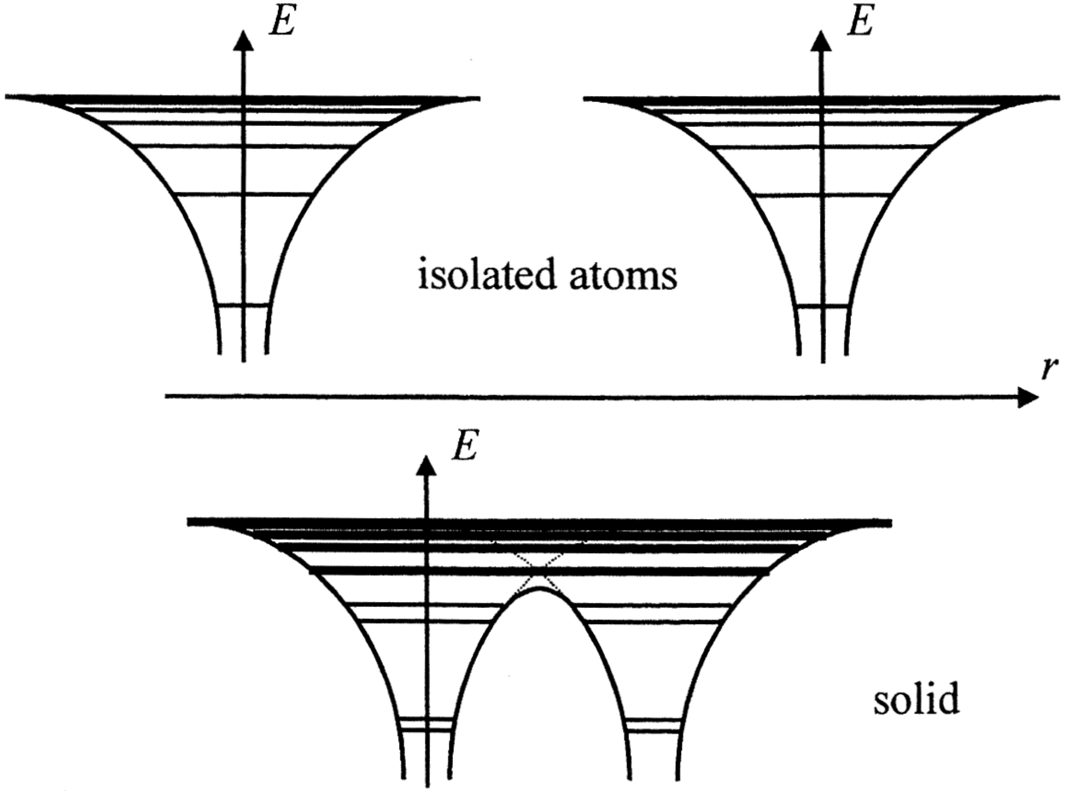
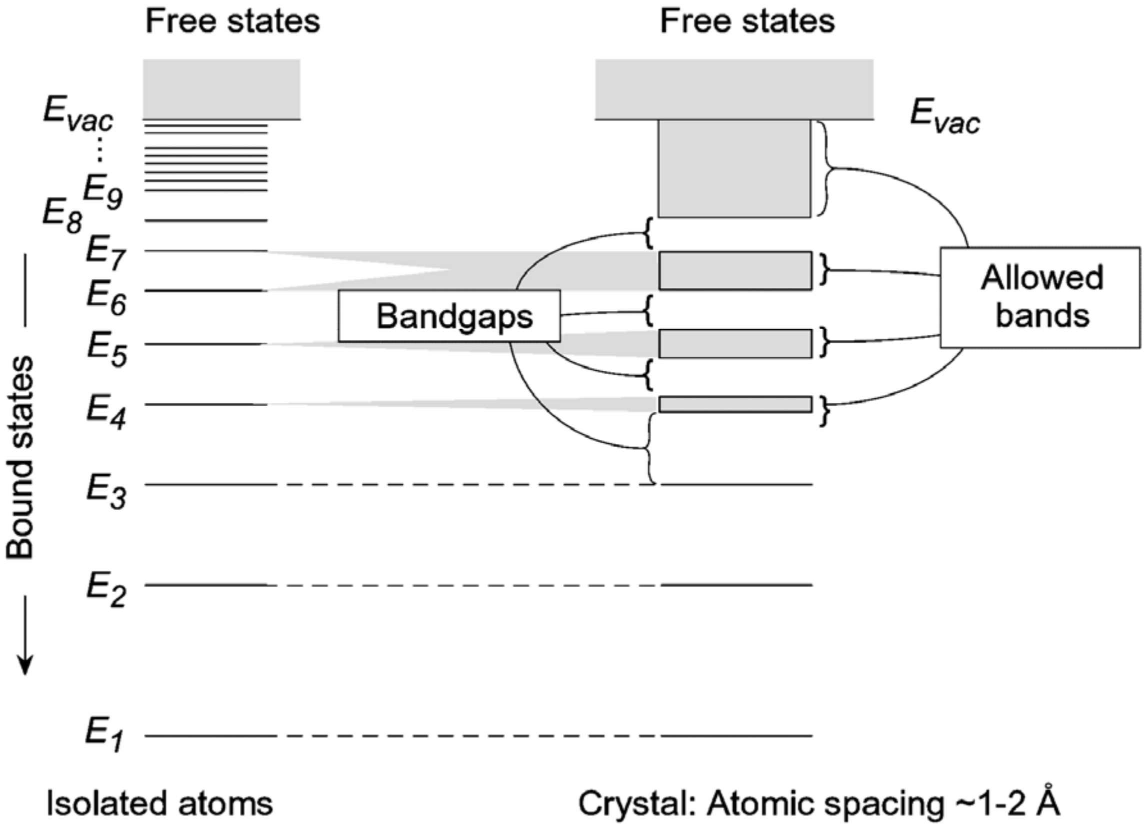


Fig. 4.10. Change in energy spectrum from single atoms to a solid. Each of the discrete energy levels in two isolated atoms split into two separate energy levels when the atoms are bound in a solid.

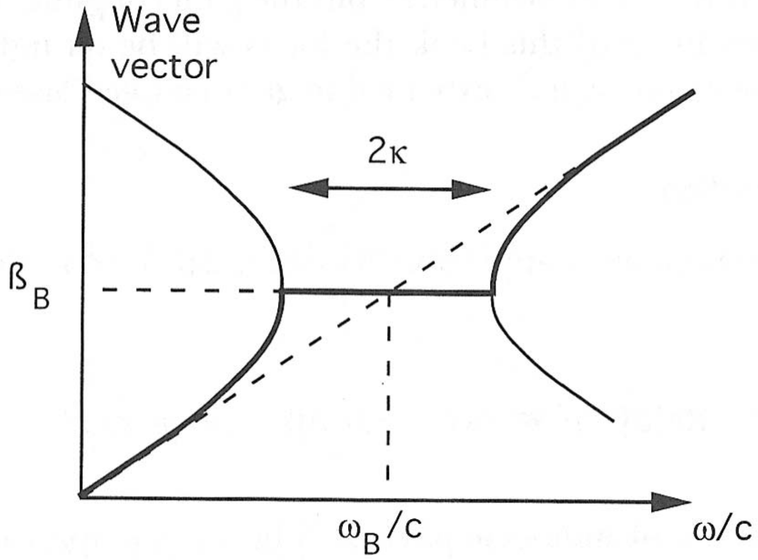
From Atomic Level to Energy Band

- As atoms are brought closer and closer to each other to form a crystal, the discrete atomic levels start to broaden to form bands of allowed energies separated by gaps. The electronic states in the allowed bands are Bloch states, i.e., they are plane wave states.

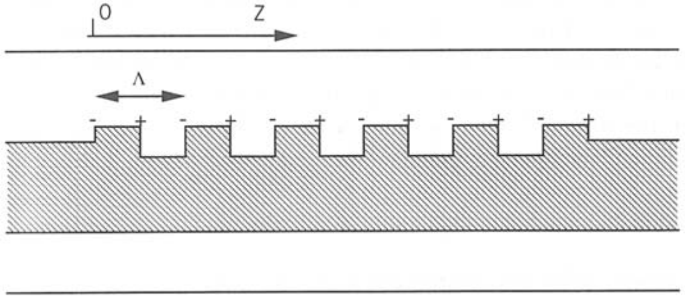


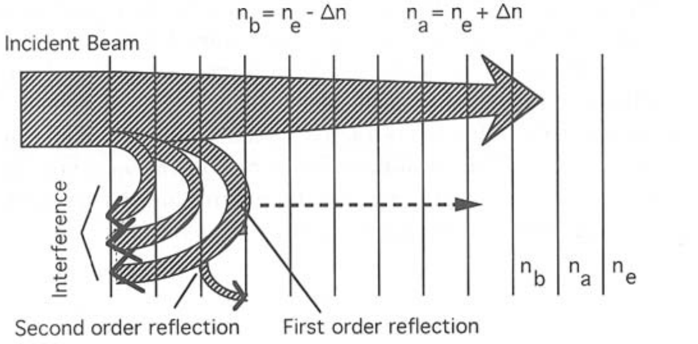
- Low lying core levels are relatively unaffected.
- Higher levels are broadened significantly to form bands.

Analogy to Photonic Crystal



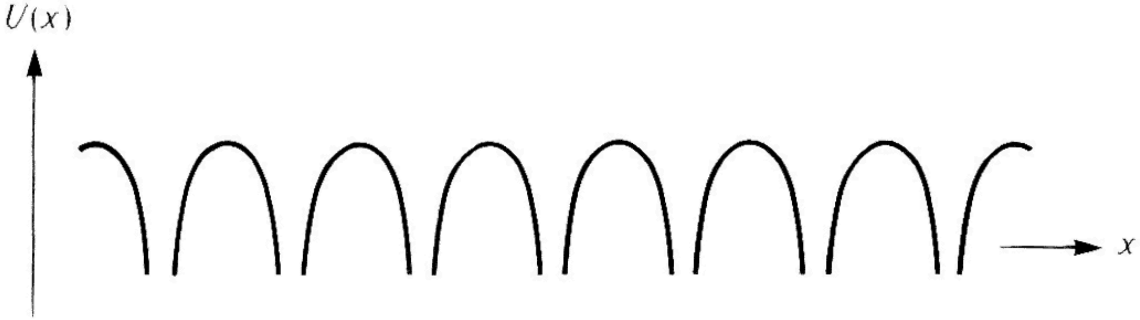
Dispersion diagram for an infinite index grating in a waveguide without loss or gain.



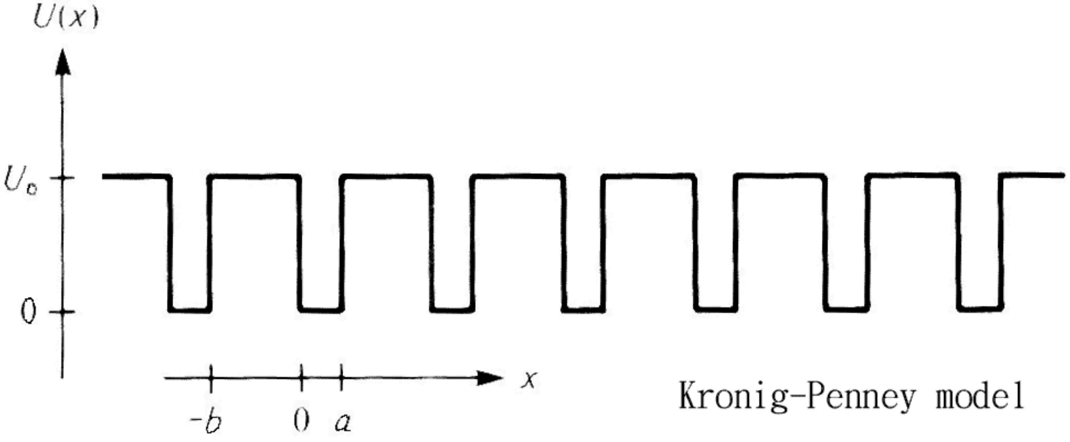


Kronig-Penney Model

- Bloch theorem need to be simplified further
- Shape of the periodic potential poses difficulties to solve SQ



One dimentioral periodical potential



Kronig-Penney model

Electron in a Crystal

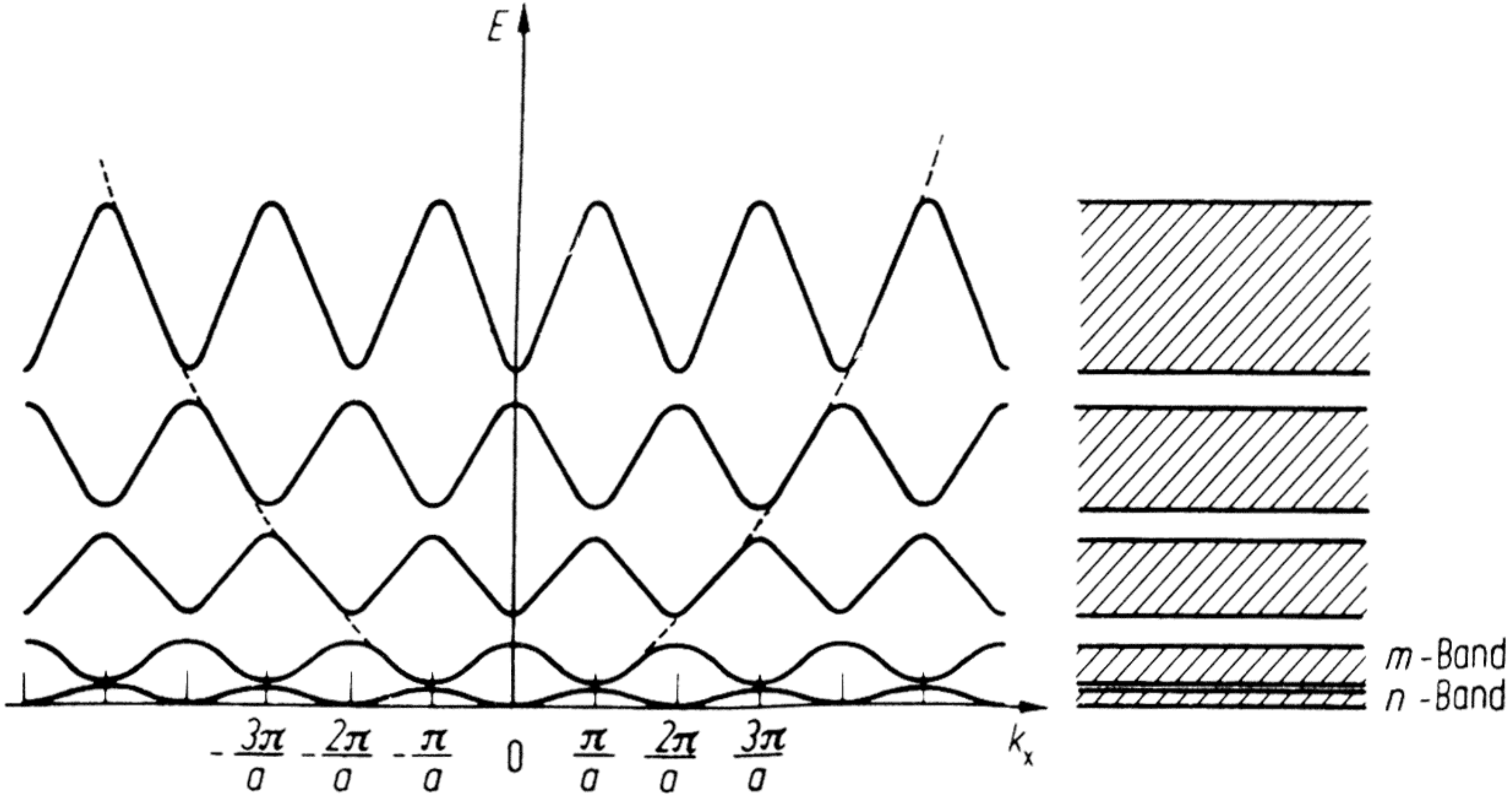
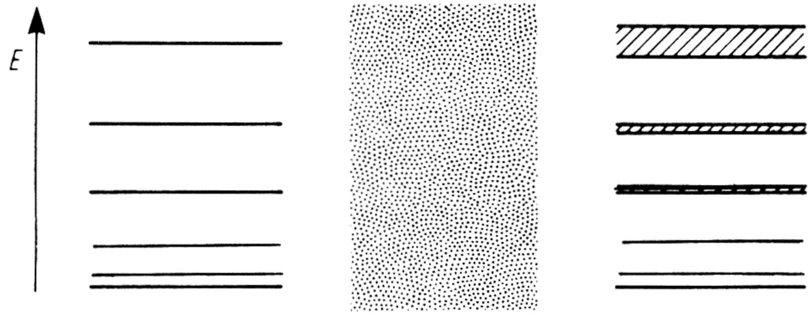


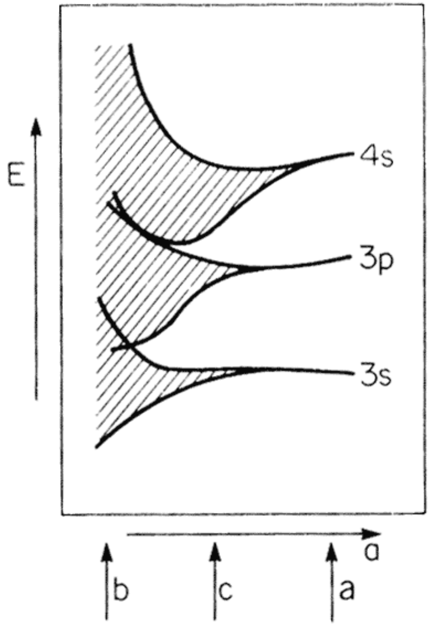
Figure 5.3. Periodic zone scheme.

Cont’



(a) (b) (c)

Figure 4.13. Allowed energy levels for (a) bound electrons, (b) free electrons, and (c) electrons in a solid.



3-D k Space

BANDSTRUCTURE OF SEMICONDUCTORS

The *k*-vector for the electrons in a crystal is limited to a space called the Brillouin zone. The figure shows the Brillouin zone for the fcc lattice relevant for most semiconductors. The values and notations of certain important *k*-points are also shown. Most semiconductors have bandedges of allowed bands at one of these points.

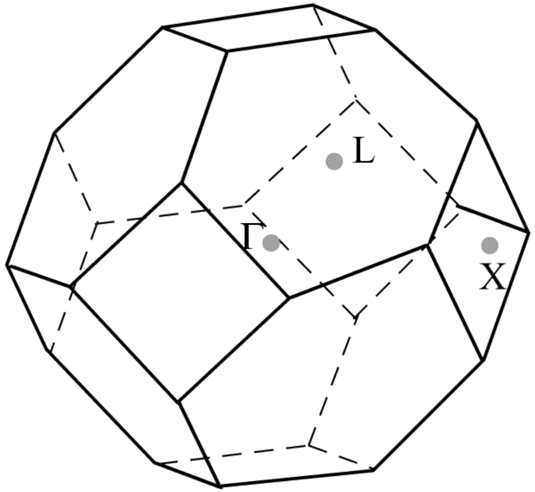
IMPORTANT HIGH SYMMETRY POINTS

Γ point: $k_x = 0 = k_y = k_z$

X point: $k_x = \frac{2\pi}{a}\,;\ k_y = k_z = 0$

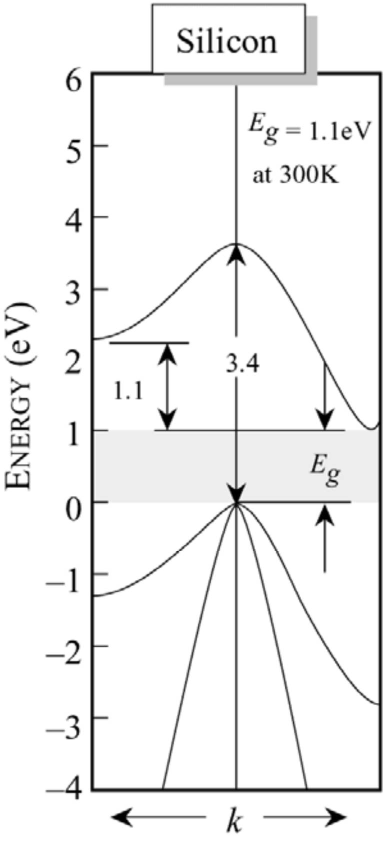
L point: $k_x = k_y = k_z = \frac{\pi}{a}$

a = lattice constant (cube edge)

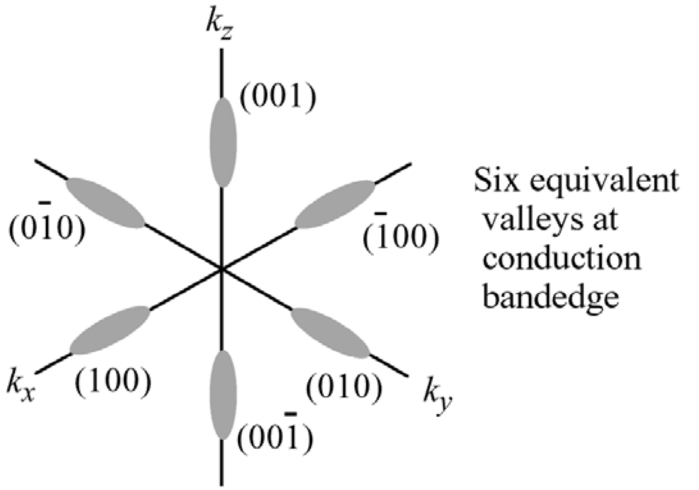


Si Band Structures

Although the bandstructure of Si is far from ideal, having an indicrect bandgap, hig hhole masses, and small spin-orbit splitting, processing related advantages make Si the premier semiconductor for consumer electronics. On the right we show constant energy ellipsoids for Si conduction band. There are six equivalent valleys in Si at the bandedge.



(a)

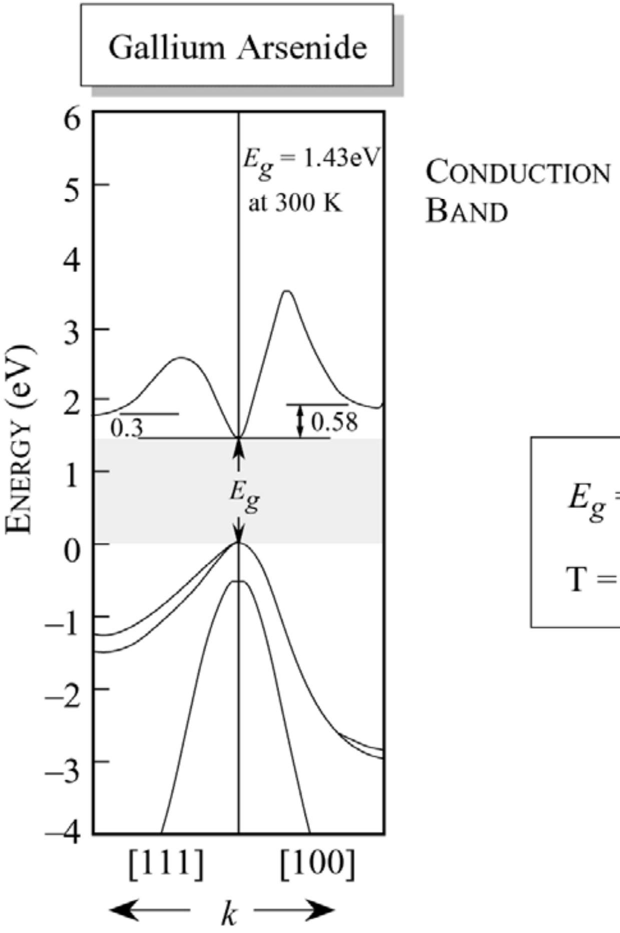


$$E_g = 1.17 - \frac{4.37 \times 10^{-4}\, T^2}{T - 636}\ \text{(eV)} \qquad T = \text{Temperature in K}$$

(b)

GaAs Band Structure

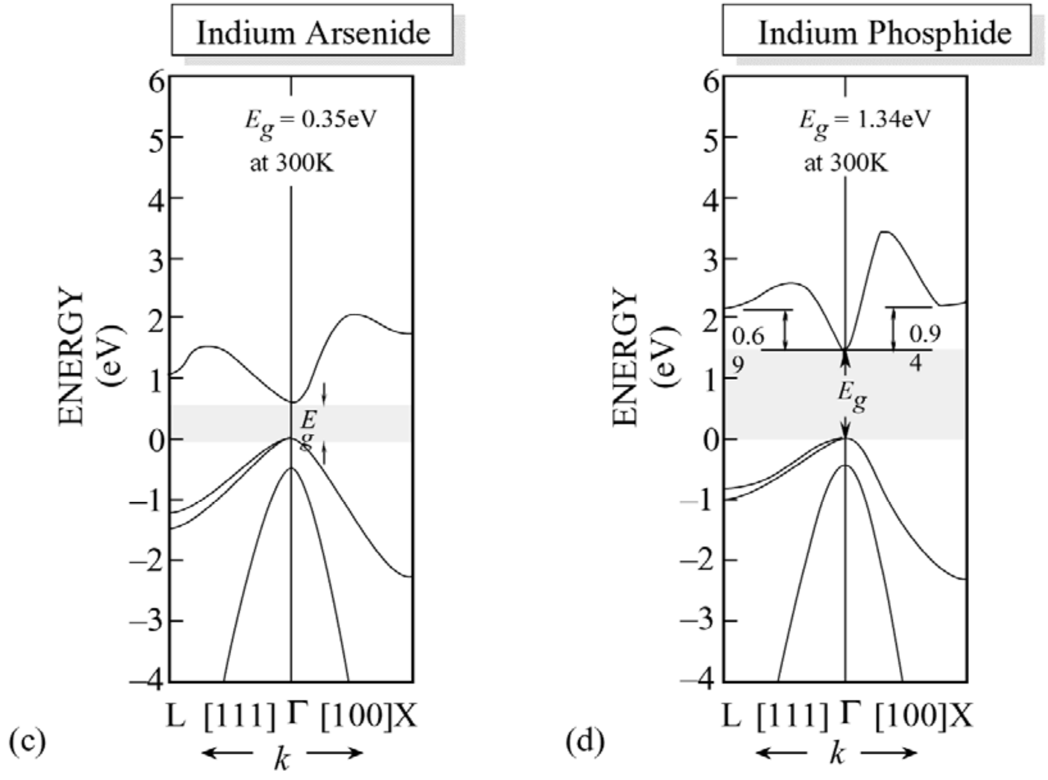
The bandgap at 0 K is 1.51 eV and at 300 K it is 1.43 eV. The bottom of the conductionband is at $k = (0,0,0)$, i.e., the G-point. The upper conduction band valleys are at the L-point.



$$E_g = 1.519 - \frac{5.4 \times 10^{-4}\, T^2}{T + 204} \text{ (eV)}$$

T = Temperature in K

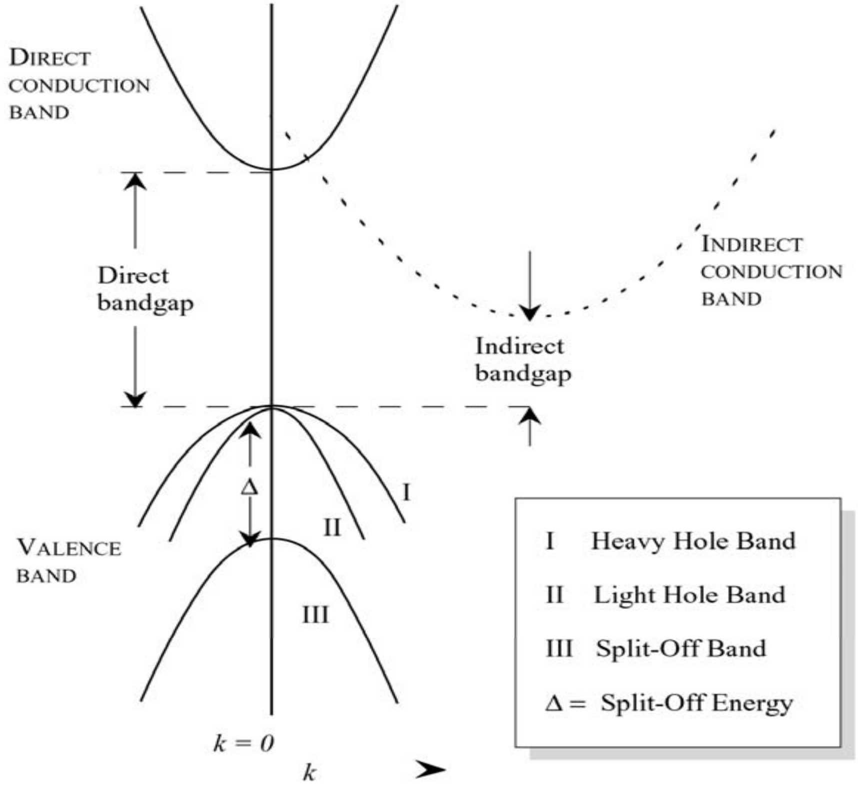
InAs, InP Band Structure



(a) Bandstructure of Ge. (b) Bandstructure of AlAs. (c) Bandstructure of InAs. Since no adequate substitute matches InAs directly, it is often used as an alloy (InGaAs, InAlAs, etc.,) for devices. (d) Bandstructure of InP. InP is a very important material for high speed devices as well as a substrate and barrier layer material for semiconductor lasers.

Band Structures Near Band Edges

Behavior of electrons near the bandedges determines most device properties. Near the bandedges the electrons can be described by simple effective mass pictures, i.e., the electrons behave as if they are in free space except their masses are m^*.



Schematic of the valence band, direct bandgap, and indirect bandgap conduction bands. The conduction band of the direct gap semiconductor is shown in the solid line, while the conduction band of the indirect semiconductor is shown in the dashed line. The curves I, II, and III in the valence band are called *heavy hole, light hole, and split-off hole states*, respectively.

E-K Plot

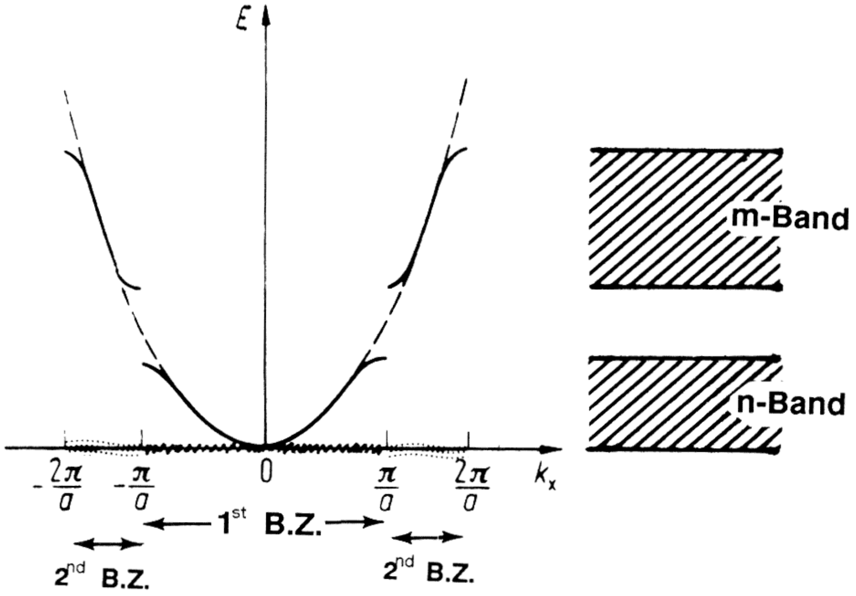
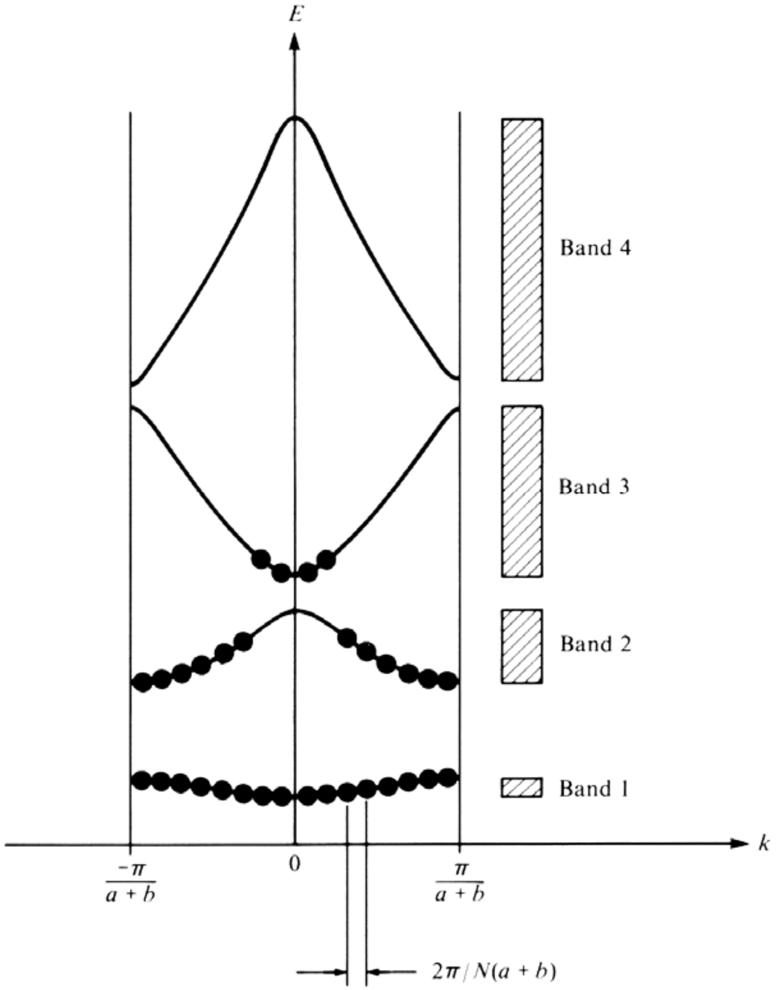


Figure 5.5. Extended zone scheme. The first and second Brillouin zones (BZ) are shown, see Section 5.2.

- dE/d*k* = 0, at the k-zone boundaries
- ħk is not the actual momentum of an electron in a crystal
  ħk includes the interaction of the electron and the crystal

Carriers



- Totally empty bands do not contribute to the charge-transport process
- Totally filled bands do not contribute to the charge-transport process
- Only partially filled bands can give rise to a net transport

What are Holes?

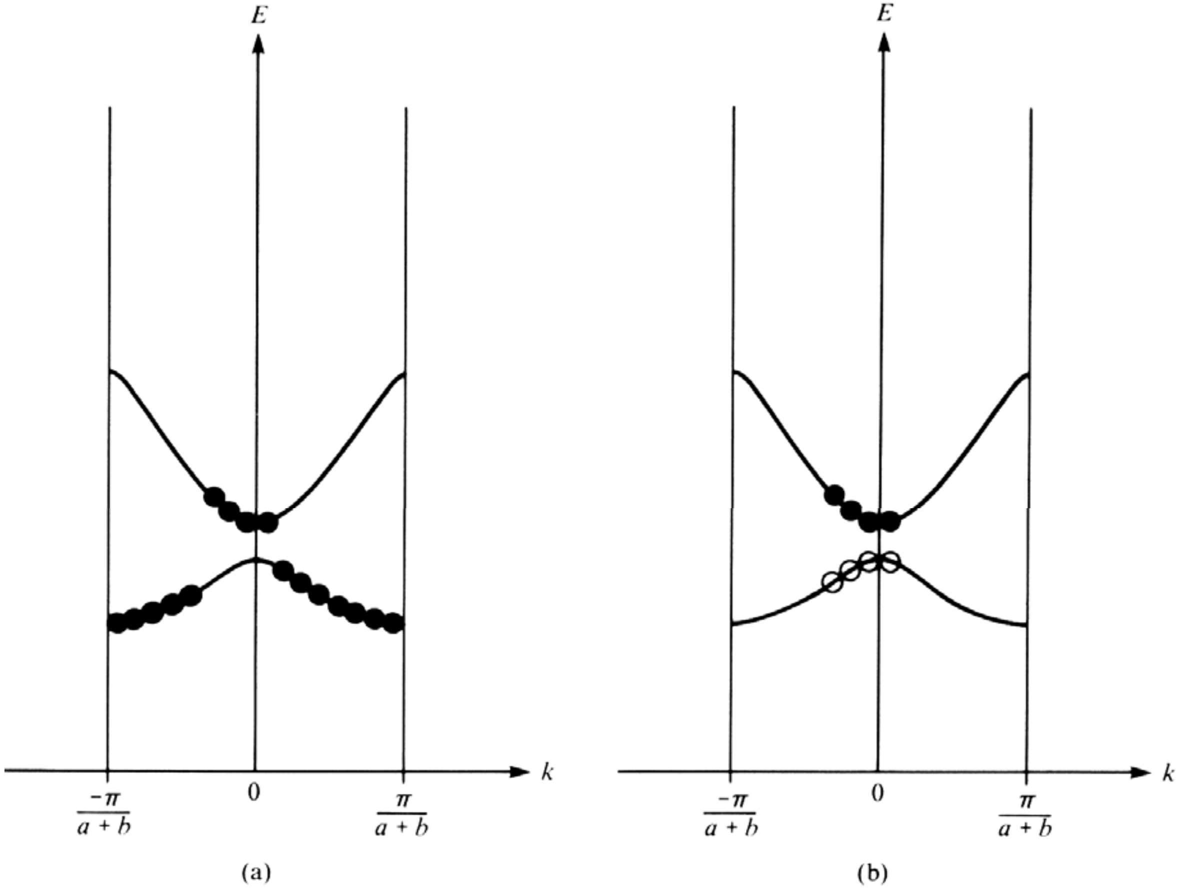
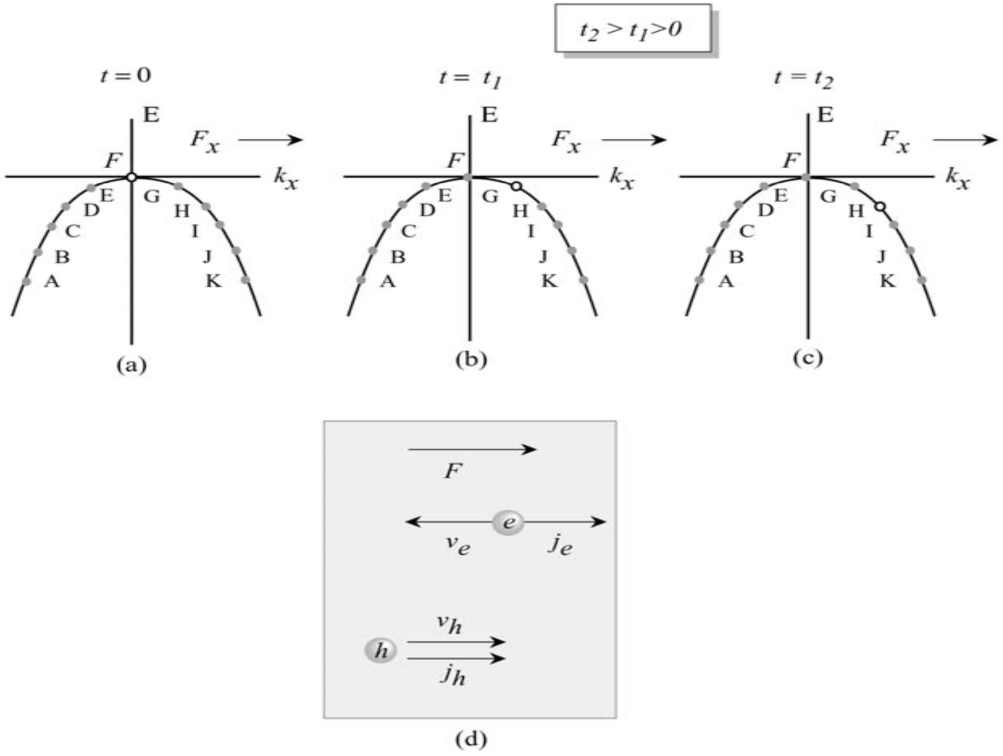
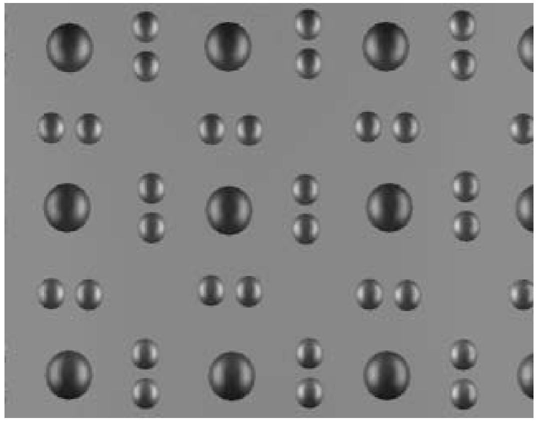


Fig. 3.11 (a) The skewed filled-state distribution under steady-state conditions subsequent to the application of an external force. (b) Introduction of the hole. Alternative description of the electronic configuration in the lower energy band.

How do Holes Move?

Holes behave *as if* they carry a positive charge.





The movement of an empty electron state, i,e,. a hole under an electric field. The electrons move in the direction opposite to the electric field so that the hole moves in the direction of the electric field thus behaving as if it were positively charged, as shown in (a), (b), and (c). (d) The velocities and currents due to electrons and holes. The current flow is in the same direction, even though the electron and holes have opposite velocities. The electron effective mass in the valence band is negative, but the hole behaves as if it has a positive mass.

Action of Particles

- Wave-Particle duality
- Heisenberg uncertainty principle

$$\Delta E \, \Delta t \geq \hbar$$
$$\Delta p_x \, \Delta x \geq \hbar$$

- Wavepacket is the quantum mechanical analogy of a classical particle localized to a given space.
- The wavepacket consists of a linear combination of constant-E wavefunction solutions closely group about a peak.

Action Modeling (effective mass)

- Reaction of the wavepacket to external forces and its spatial evolution with time provide the equation of motion for an electron in a crystal.

$$\boxed{F = m^* \frac{dv_g}{dt}}$$

- The equation is identical to Newton's second low of motion except that the actual particle mass is replaced by an *effective mass m^*.* This implies that the motion of electrons in a crystal can be visualized and described in a quasi-classical manner.

$$\boxed{m^* \equiv \frac{1}{\frac{1}{\hbar^2}\frac{d^2E}{dk^2}}}$$

- Because of this simplification, device analyses can often be completed with minimal direct use of the quantum mechanical formalism, unless you want to calculate the band structure.

Effective Mass

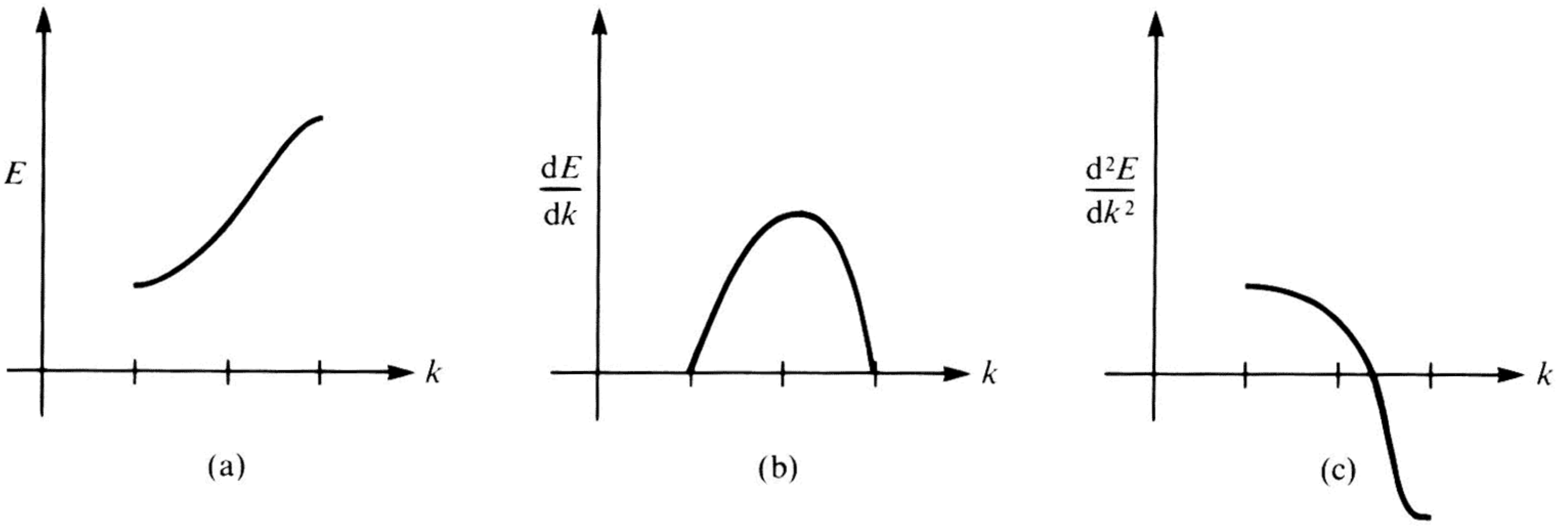
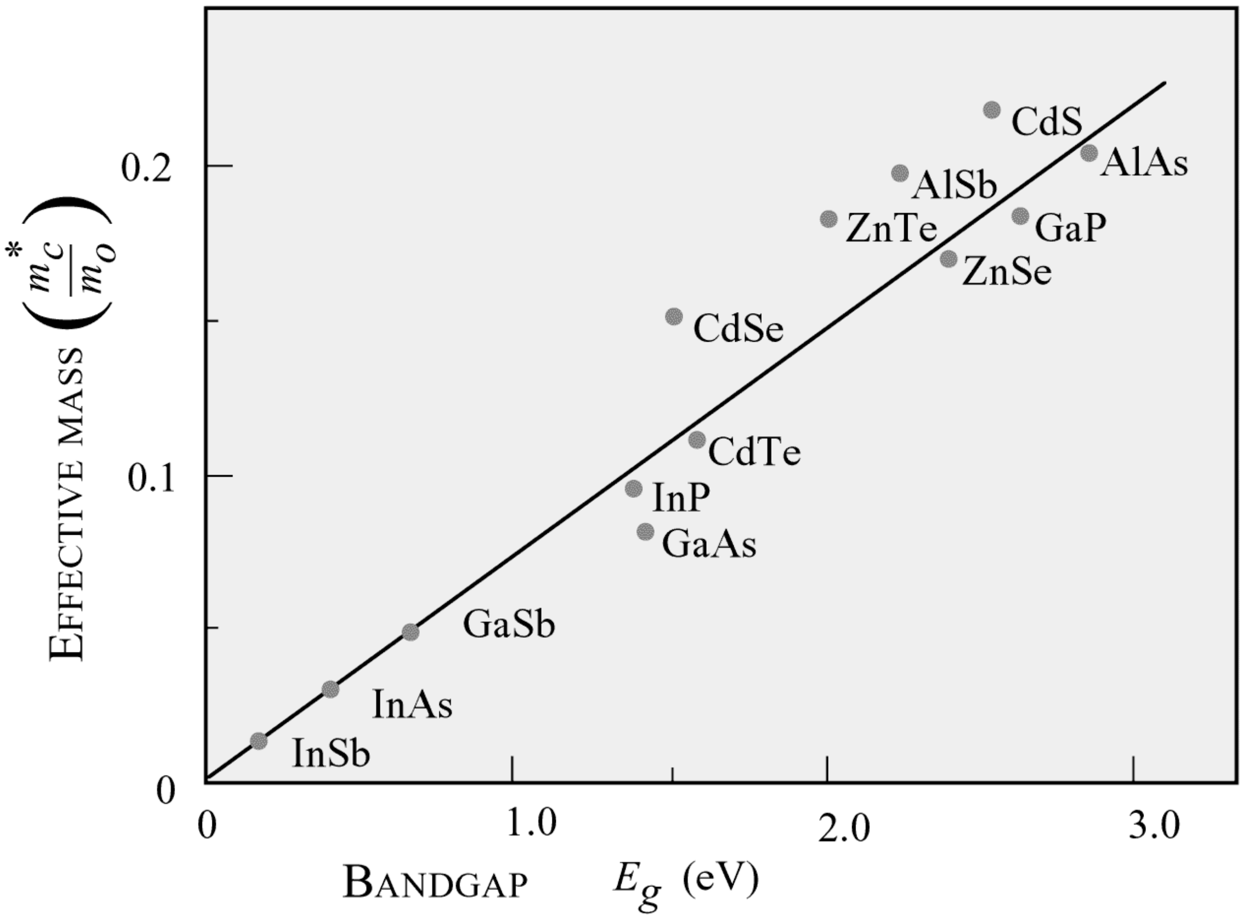


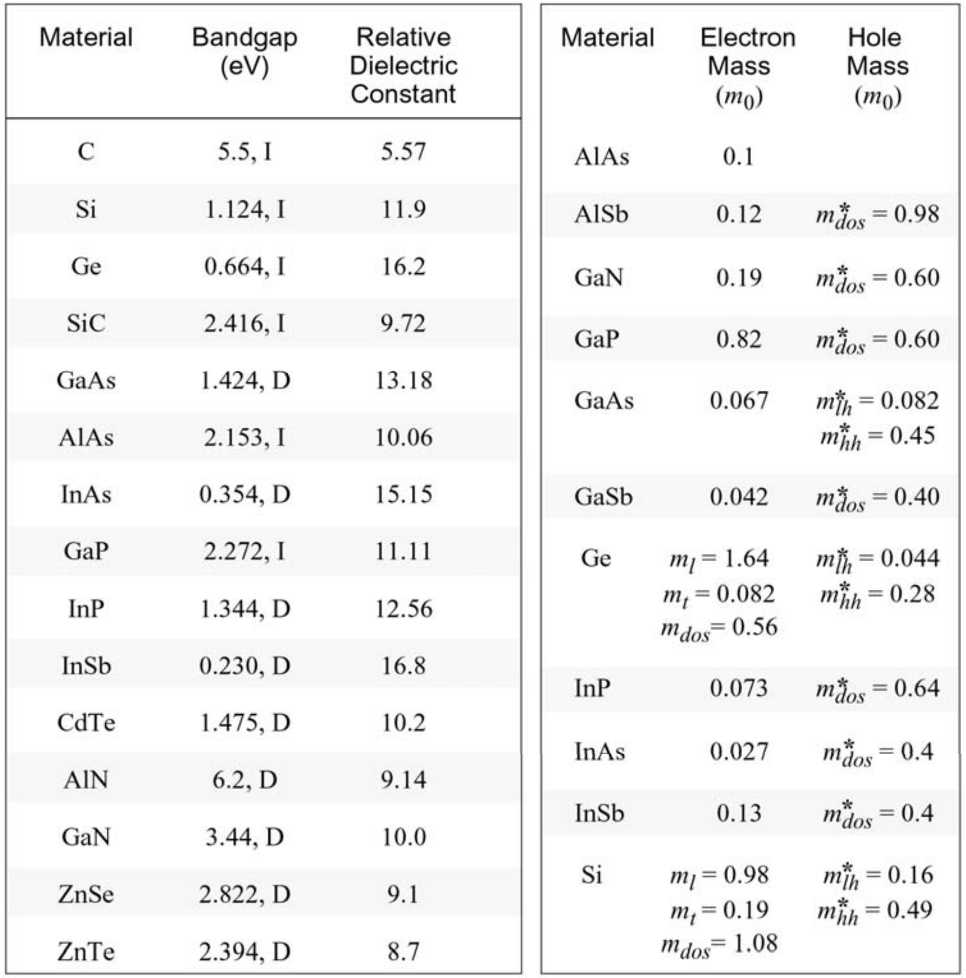
Fig. 3.8 Deducing the sign of the effective-mass factor. (a) Sample band segment. (b) Graphically deduced first derivative and (c) second derivative of energy with respect to wavenumber.

- Carriers in a crystal with energies near the top or bottom of an energy band typically exhibit a CONSTANT effective mass.

Effective Mass



Electronic Properties



Material	Bandgap (eV)	Relative Dielectric Constant
C	5.5, I	5.57
Si	1.124, I	11.9
Ge	0.664, I	16.2
SiC	2.416, I	9.72
GaAs	1.424, D	13.18
AlAs	2.153, I	10.06
InAs	0.354, D	15.15
GaP	2.272, I	11.11
InP	1.344, D	12.56
InSb	0.230, D	16.8
CdTe	1.475, D	10.2
AlN	6.2, D	9.14
GaN	3.44, D	10.0
ZnSe	2.822, D	9.1
ZnTe	2.394, D	8.7

Material	Electron Mass (m_0)	Hole Mass (m_0)
AlAs	0.1	
AlSb	0.12	$m^*_{dos} = 0.98$
GaN	0.19	$m^*_{dos} = 0.60$
GaP	0.82	$m^*_{dos} = 0.60$
GaAs	0.067	$m^*_{lh} = 0.082$ $m^*_{hh} = 0.45$
GaSb	0.042	$m^*_{dos} = 0.40$
Ge	$m_l = 1.64$ $m_t = 0.082$ $m_{dos} = 0.56$	$m^*_{lh} = 0.044$ $m^*_{hh} = 0.28$
InP	0.073	$m^*_{dos} = 0.64$
InAs	0.027	$m^*_{dos} = 0.4$
InSb	0.13	$m^*_{dos} = 0.4$
Si	$m_l = 0.98$ $m_t = 0.19$ $m_{dos} = 1.08$	$m^*_{lh} = 0.16$ $m^*_{hh} = 0.49$

Properties of some semiconductors. D and I stand for direct and indirect gap, respectively. The data are at 300 K. Note that Si has six conducton band valleys, while Ge has four.

Energy Band Model

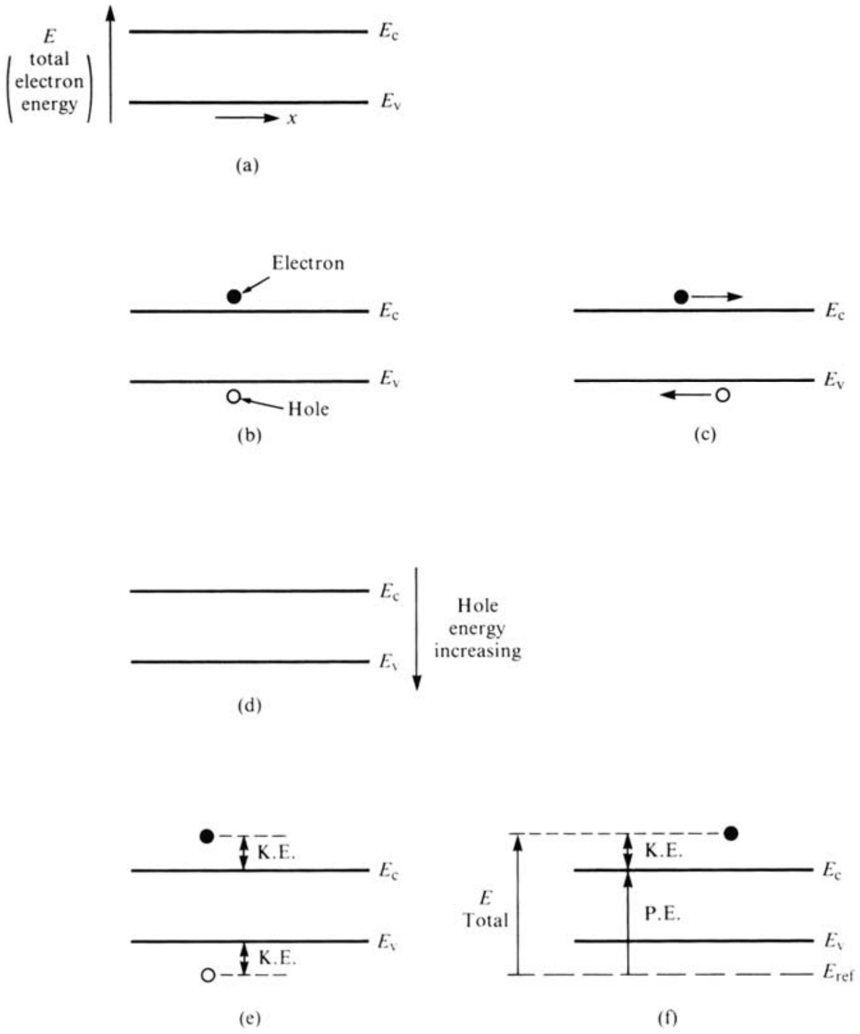


Fig. 4.8 The energy band model or diagram. (a) Basic diagram. (b) Representation of carriers. (c) Representation of carrier motion. Diagram interpretation of (d) increasing hole energies, (e) carrier kinetic energies, and (f) the carrier potential energy.

Band Bending

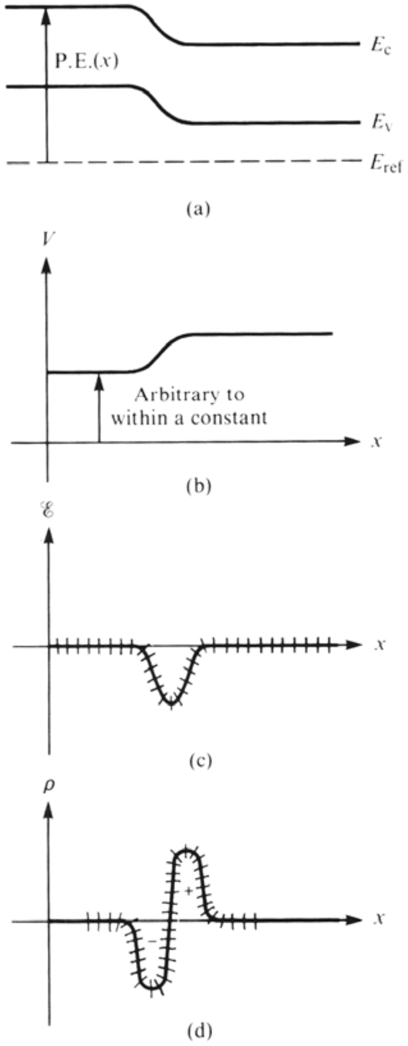
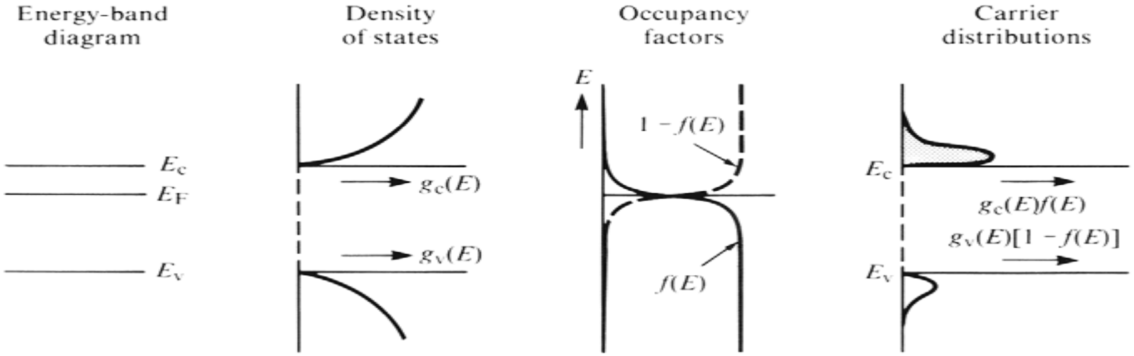


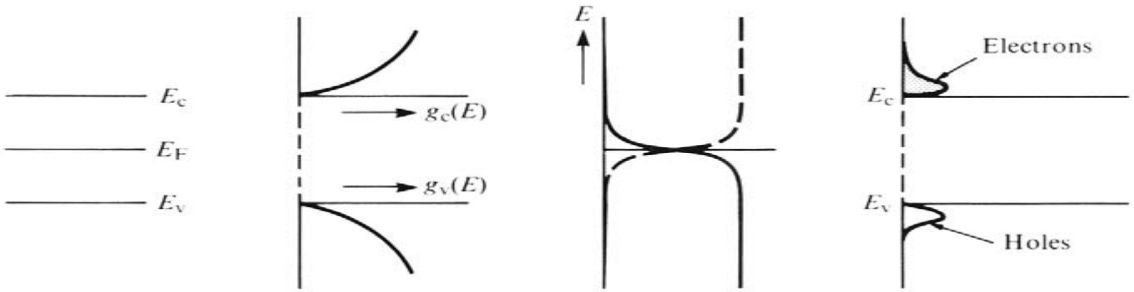
Fig. 4.9 Relationship between "band bending" and the electrostatic variables inside a semiconductor. (a) Sample energy band diagram exhibiting band bending. (b) Electrostatic potential, (c) electric field, and (d) charge density versus position deduced from and associated with the part (a) diagram.

Carrier Statistics

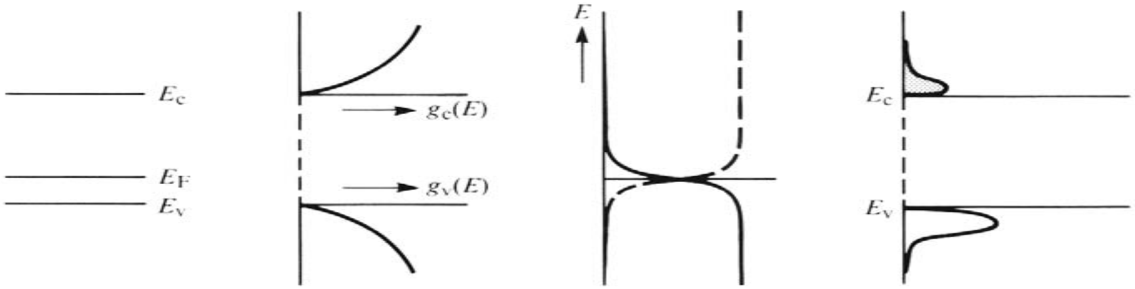
Carrier Distributions



(a) E_F above midgap



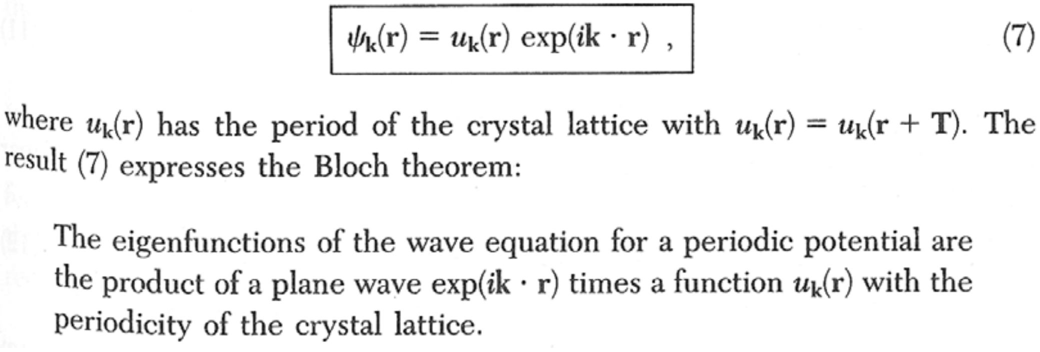
(b) E_F near midgap



(c) E_F below midgap

3-D Density of States

- Apply Bloch Theorem



$$\boxed{\psi_{\mathbf{k}}(\mathbf{r}) = u_{\mathbf{k}}(\mathbf{r}) \exp(i\mathbf{k} \cdot \mathbf{r}) \ ,} \tag{7}$$

where $u_{\mathbf{k}}(\mathbf{r})$ has the period of the crystal lattice with $u_{\mathbf{k}}(\mathbf{r}) = u_{\mathbf{k}}(\mathbf{r} + \mathbf{T})$. The result (7) expresses the Bloch theorem:

> The eigenfunctions of the wave equation for a periodic potential are the product of a plane wave $\exp(i\mathbf{k} \cdot \mathbf{r})$ times a function $u_{\mathbf{k}}(\mathbf{r})$ with the periodicity of the crystal lattice.

- For non-infinite crystals, the wavefunction is the same at the opposite end of the crystal

$$\Psi(x + L_x, y, z) = \Psi(x, y + L_y, z) = \Psi(x, y, z + L_z) = \Psi(x, y, z)$$

Using the Bloch theorem, this conditions means that:

$$\exp(ik_x L_x) = \exp(ik_y L_y) = \exp(ik_z L_z) = 1$$

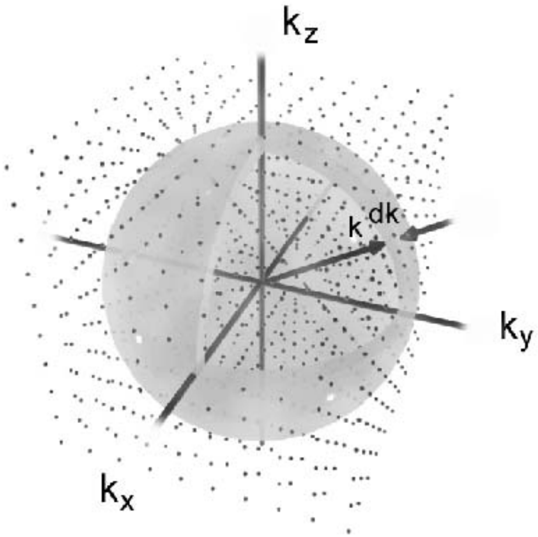
or:

$$\begin{cases} k_x = \dfrac{2\pi}{L_1} n_x \\ k_y = \dfrac{2\pi}{L_2} n_y \\ k_z = \dfrac{2\pi}{L_3} n_z \end{cases}$$

Cont'

let $\rho(K)dK$ be the number of states per unit volume between K and $K + dK$, then

$$\begin{aligned}\rho(K)dK &= \frac{4\pi K^2 dK}{(2\pi)^3/L_x L_y L_z} \times \frac{1}{V} \times 2 \\ &= \frac{K^2}{\pi^2}dK,\end{aligned}$$



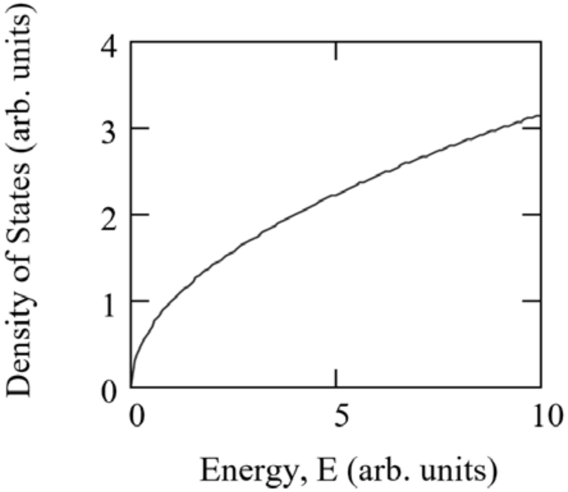
where $V = L_x L_y L_z$ is the crystal volume and we have multiplied the number of (n, m, ℓ) points in the wave vector space by a factor of 2 to take into account the fact that there can be two electrons (one with spin up and the other with spin down) occupying the state $\bar{K}$. To calculate the number of states between energies E and $E + dE$, we use the fact that

$$\rho(K)dK = \rho(E)dE.$$

and parabolic approx

Therefore,

$$\begin{aligned}\rho(E) &= \rho(K)\frac{dK}{dE} \\ &= \frac{K^2}{\pi^2} \times \frac{m}{\hbar^2 K} = \frac{mK}{\pi^2\hbar^2} \\ &= \frac{m}{\pi^2\hbar^2}\left(\frac{2mE}{\hbar^2}\right)^{1/2} \\ &\boxed{= \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2} E^{1/2}}\end{aligned}$$



Note that if the origin of the energies has not been chosen to be the bottom of the band, then ***E*** would be replaced by $E - E_c$

Density of States Effective Masses

- The effective mass used in the density of states expression must be some combination, an appropriate "average" of the band-structure effective masses.

Holes

$$m_p^* = [(m_{hh}^*)^{3/2} + (m_{\ell h}^*)^{3/2}]^{2/3}$$

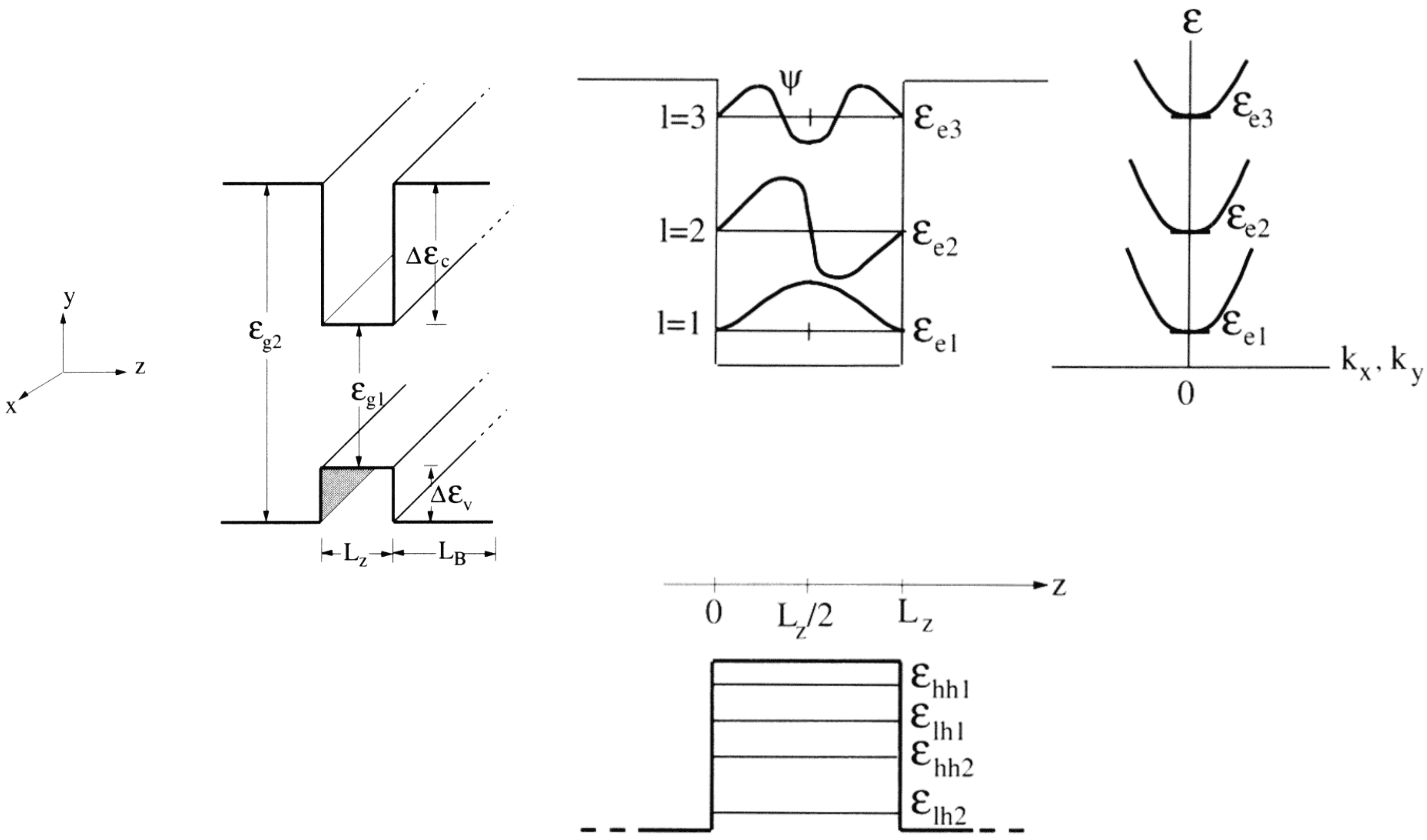
Electrons

$$m_n^* = m_e^* \qquad \ldots \text{GaAs}$$

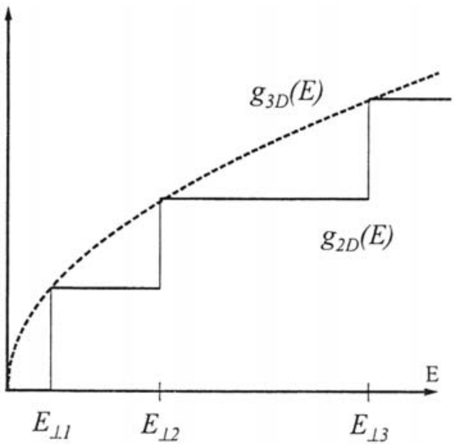
$$m_n^* = 6^{2/3}(m_\ell^* m_t^{*2})^{1/3} \qquad \ldots \text{Si}$$

$$m_n^* = 4^{2/3}(m_\ell^* m_t^{*2})^{1/3} \qquad \ldots \text{Ge}$$

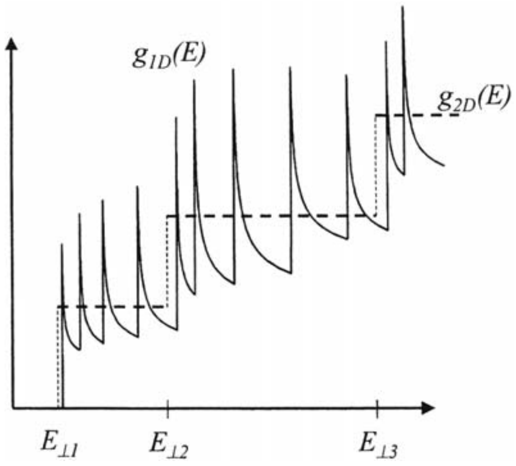
2-D Density of States



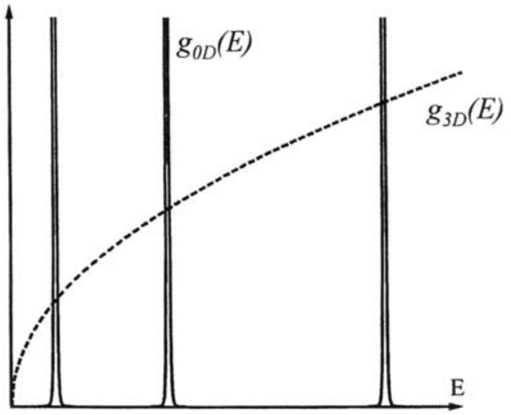
Comparison



Quantum Well



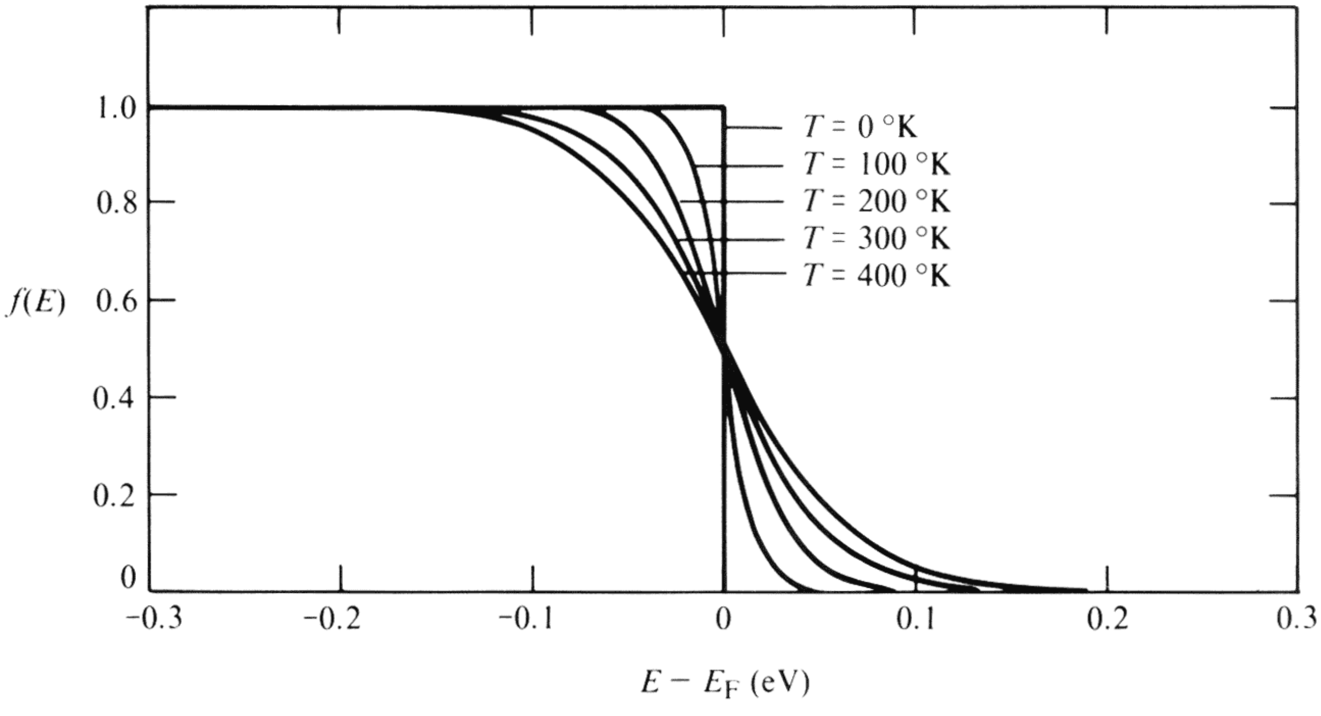
Quantum Wire



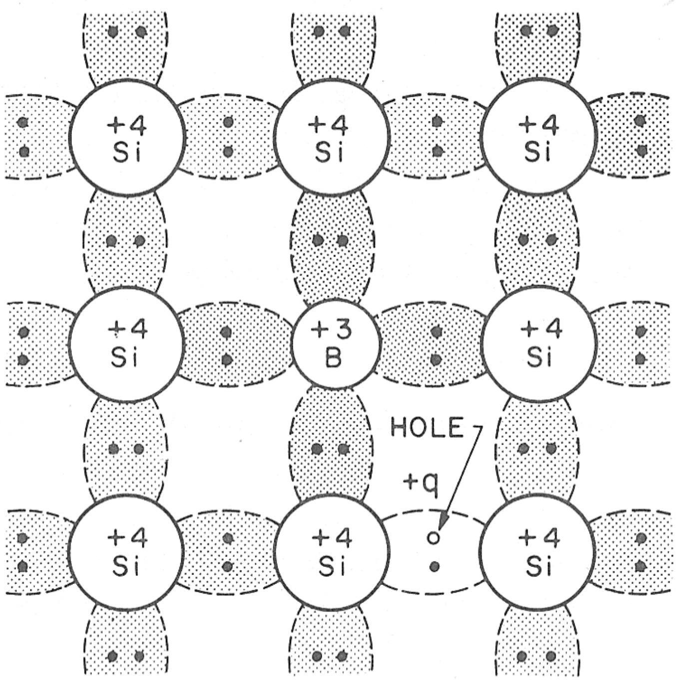
Quantum Dot

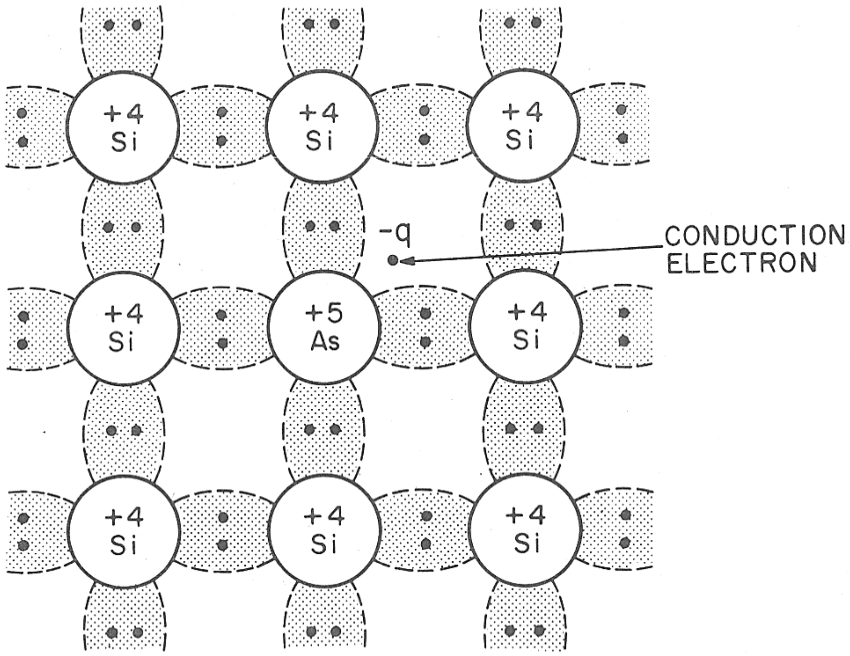
Energy Distribution Functions

$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

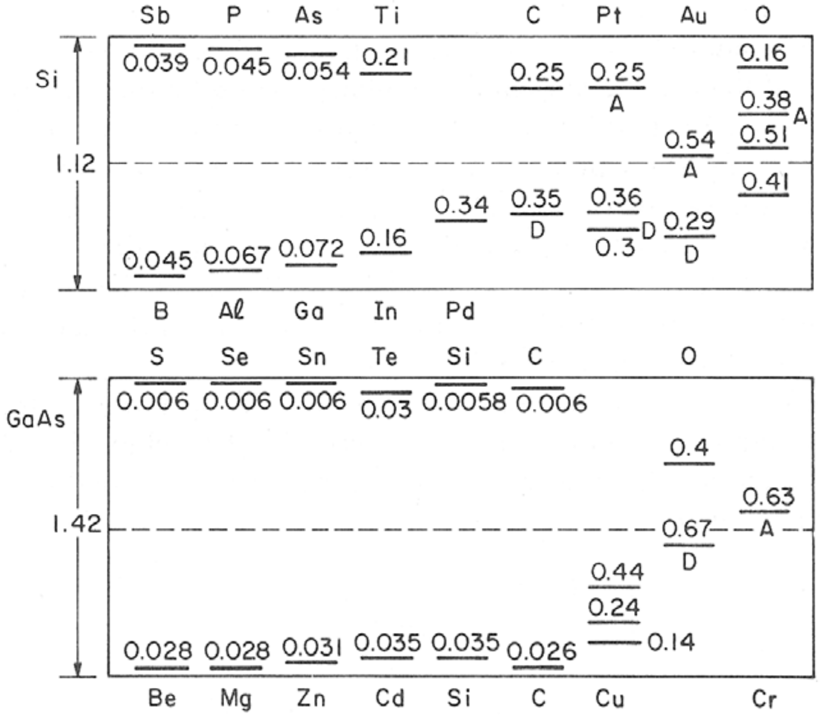


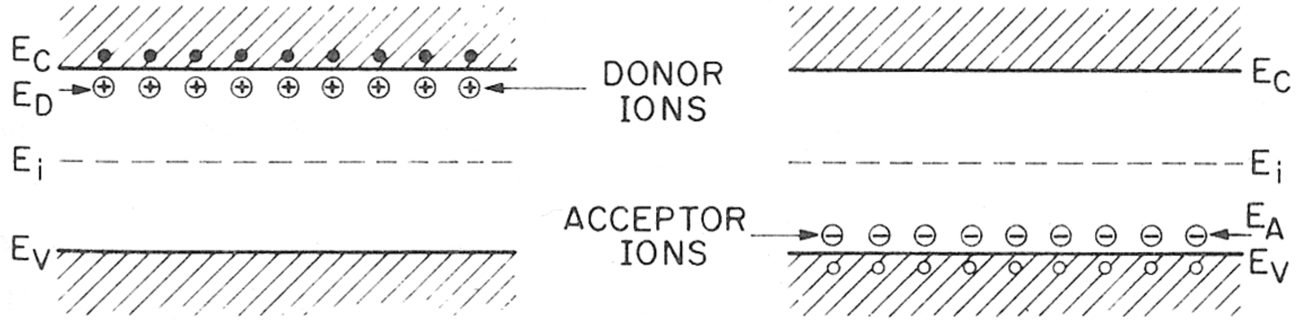
Extrinsic Semiconductor





Dopants


Sb
P
As
Ti
C
Pt
Au
O
Si
0.039
0.045
0.054
0.21
0.25
0.25
A
0.16
0.38
A
0.51
0.54
A
1.12
0.41
0.34
0.35
D
0.36
D
0.3
0.29
D
0.045
0.067
0.072
0.16
B
Aℓ
Ga
In
Pd
S
Se
Sn
Te
Si
C
O
GaAs
0.006
0.006
0.006
0.03
0.0058
0.006
0.4
0.63
1.42
0.67
A
D
0.44
0.24
0.14
0.028
0.028
0.031
0.035
0.035
0.026
Be
Mg
Zn
Cd
Si
C
Cu
Cr


E$_C$
E$_D$
DONOR IONS
E$_i$
E$_V$
E$_C$
E$_i$
ACCEPTOR IONS
E$_A$
E$_V$

Temperature Dependency

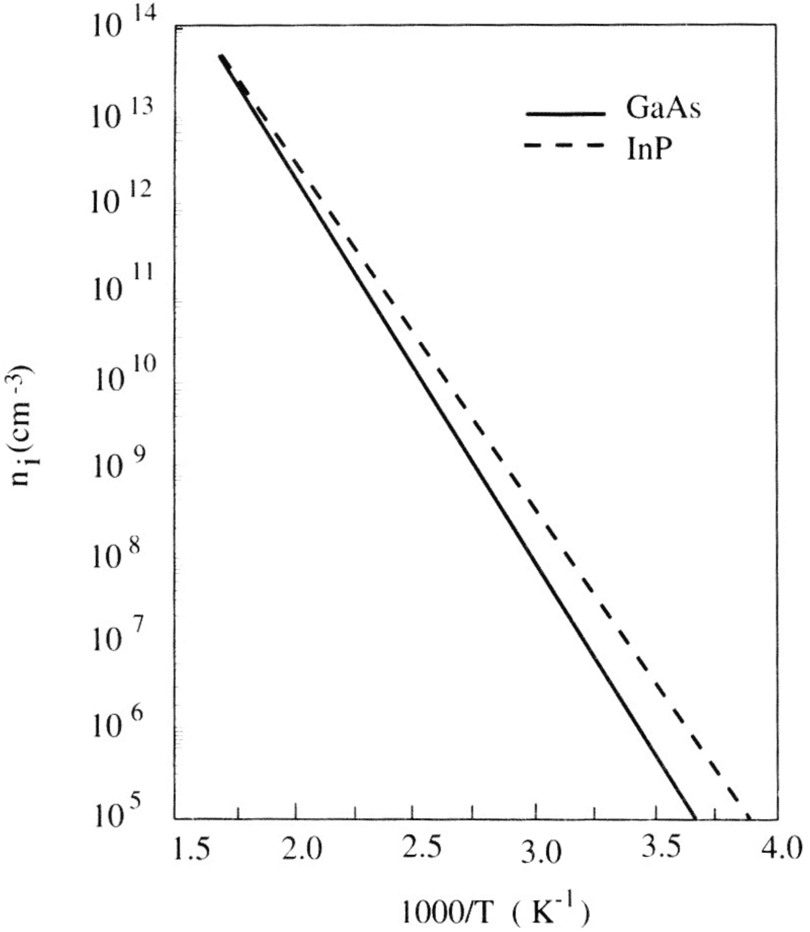


Figure 2.17 Intrinsic carrier concentration for GaAs and InP as a function of inverse temperature.

Temperature Dependency

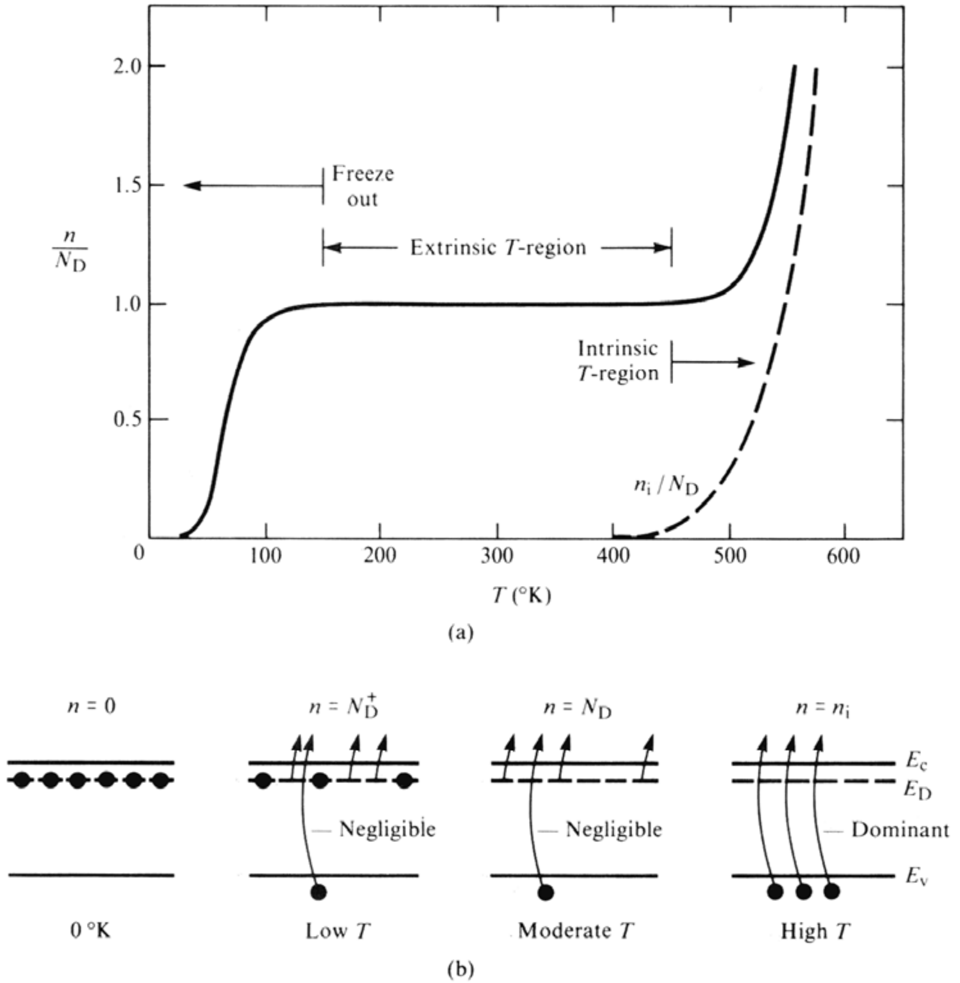


Fig. 4.18 (a) Typical temperature dependence of the majority-carrier concentration in a doped semiconductor. The plot was constructed assuming a phosphorus-doped $N_D = 10^{15}/\text{cm}^3$ Si sample. n_i/N_D versus T (dashed line) has been included for comparison purposes. (b) Qualitative explanation of the concentration-versus-temperature dependence displayed in part (a).

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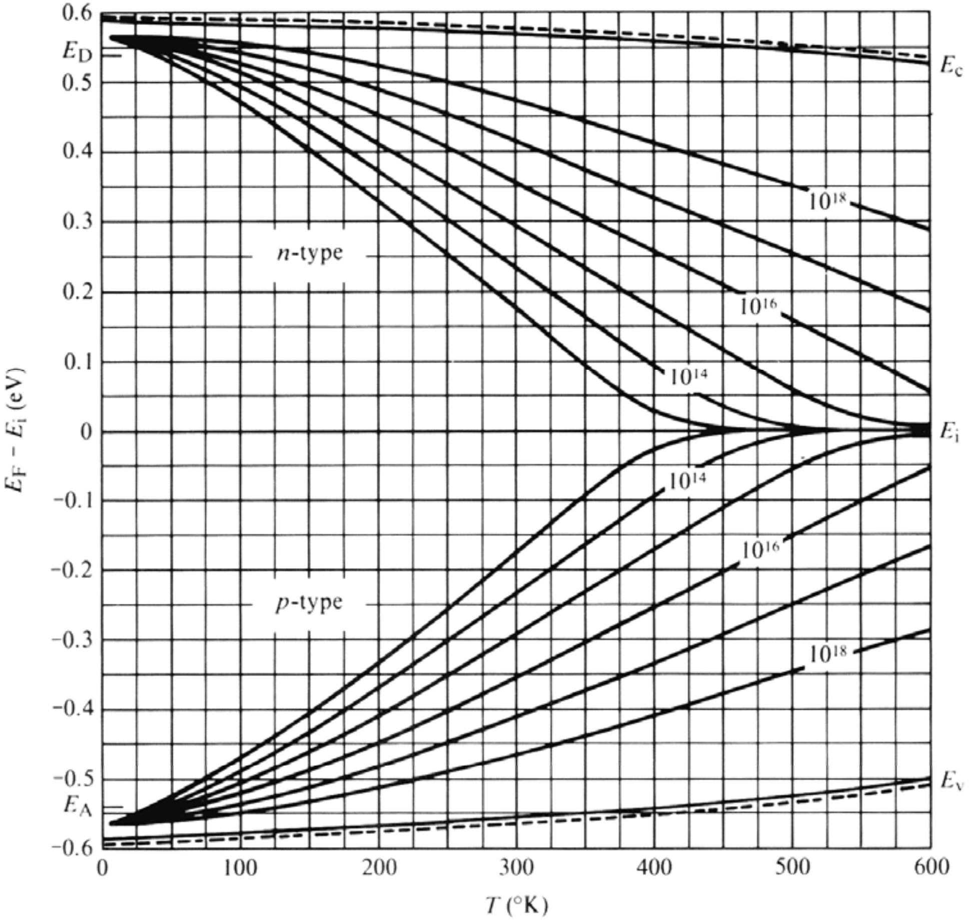


Fig. 4.19 Fermi level positioning in Si as a function of temperature for selected doping concentrations. The doping concentrations chosen span the range from the minimum readily attainable in Si to the degenerate limit. The dopant ionization energies were taken to be 0.045 eV, $g_D = 2$, $g_A = 4$, and the Si was assumed to contain only one type of dopant. (After Grove.[5] Reproduced with permission.)

Compensation

- A semiconductor in which the number of free carriers produced by one type of dopant is reduced by the presence of the other type of dopant
- $n_o = N_D - N_A$, $p_o = N_A - N_D$
- Compensation ratio < 0.1
- Charge neutrality: $n_o + N_A^- = p_o + N_D^+$

Heavy Doping (Degenerate)

- The Fermi level approaches the band
- The density of states function are perturbed, resulting in bandtail states
- Bandgap narrowing which would change the laser operation

$$E_g = 1.424 - 1.6 \times 10^{-8} (p^{1/3} + n^{1/3}) \text{ (eV)}$$

- When Fermi level is within the conduction or valence bands, the ionization energy of the impurity center, donors, or acceptors goes to zero. The free-carrier concentration becomes temperature-independent and all the impurity centers are ionized. The discrete impurity levels broaden into bands.

Degeneracy of Semiconductor

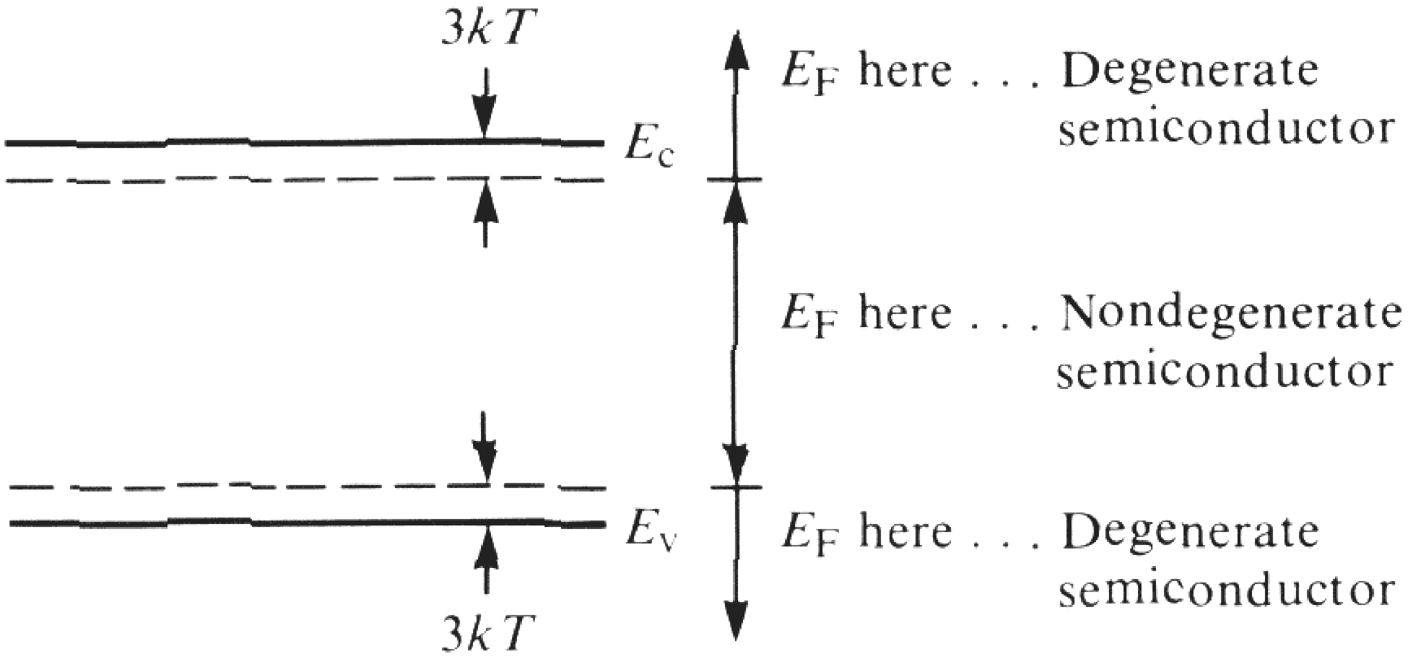
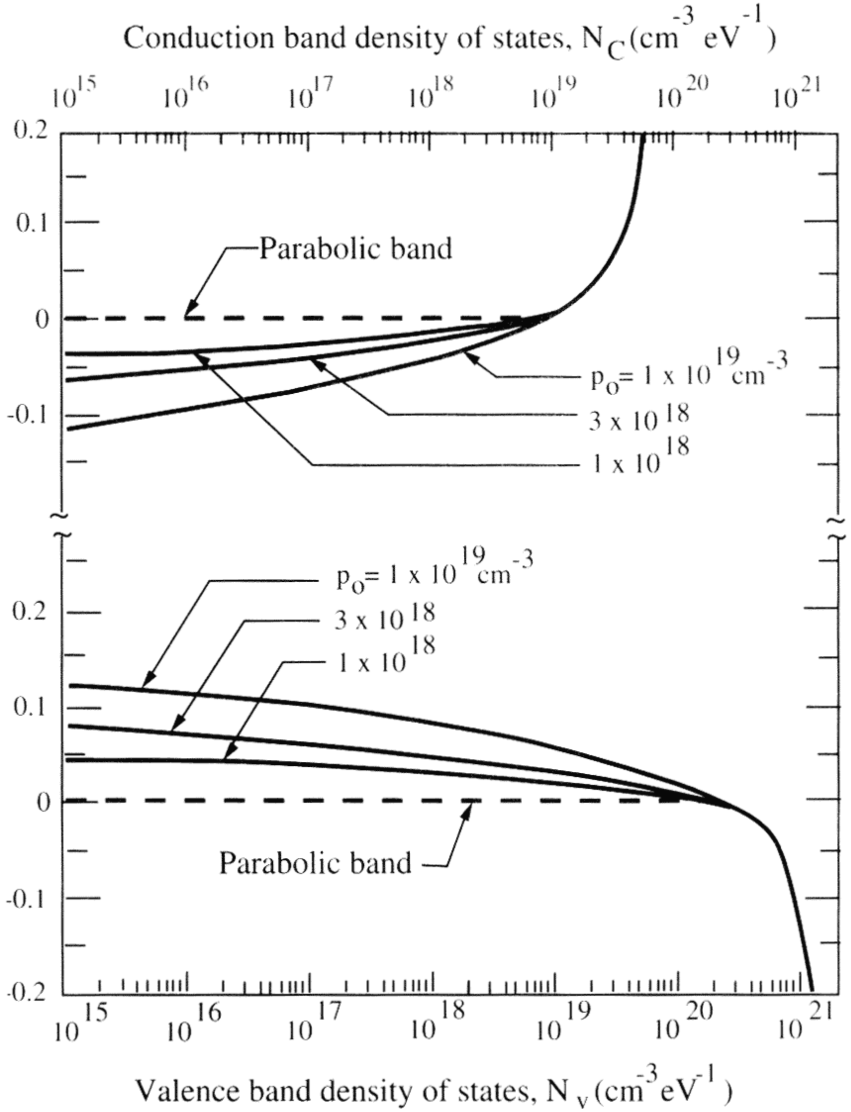


Fig. 4.16 Definition of degenerate/nondegenerate semiconductors.

Bandtail


Conduction band density of states, N_C (cm^{-3} eV^{-1})
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
0.2
0.1
0
-0.1
Parabolic band
$p_o = 1 \times 10^{19}$ cm^{-3}
3×10^{18}
1×10^{18}
$p_o = 1 \times 10^{19}$ cm^{-3}
3×10^{18}
1×10^{18}
0.2
0.1
0
-0.1
-0.2
Parabolic band
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Valence band density of states, N_v (cm^{-3}eV^{-1})

Cont’

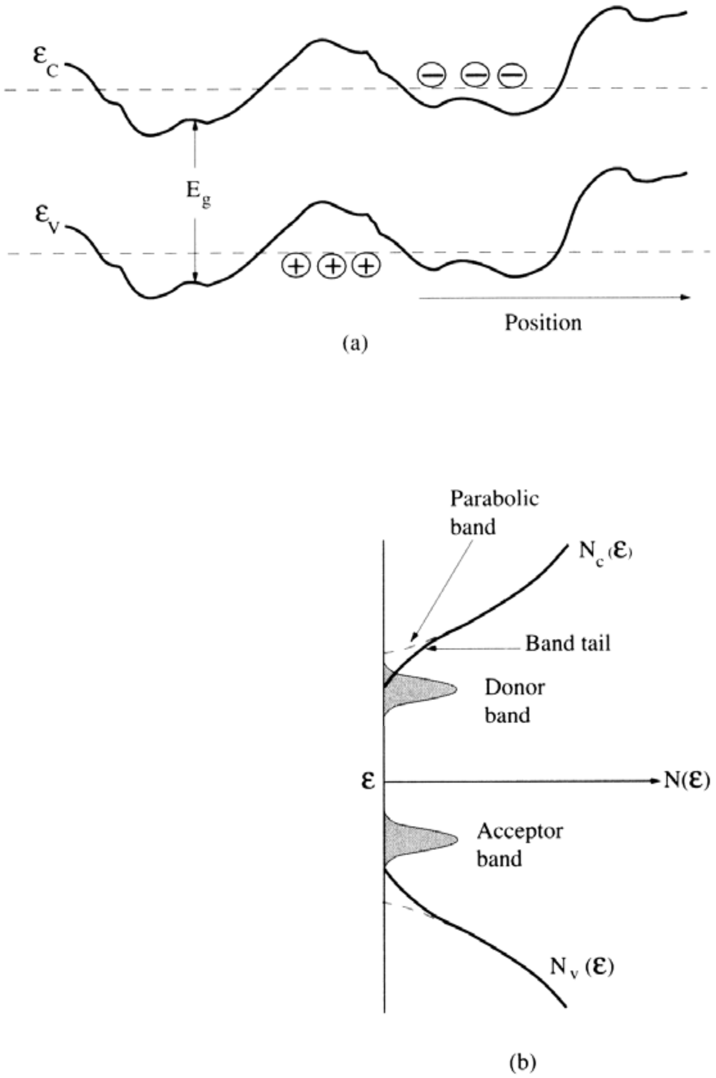
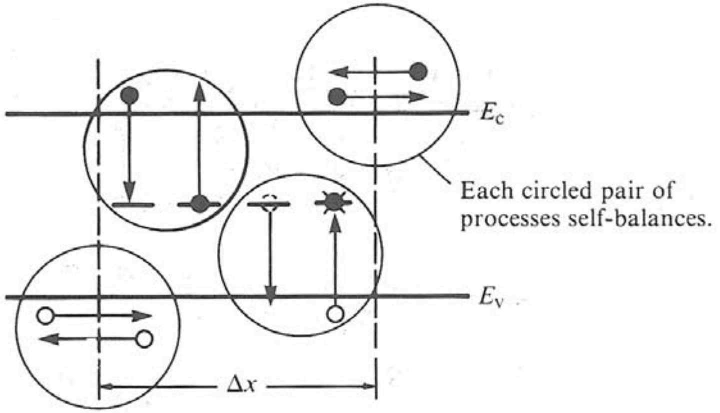


Figure 2.24 Schematic illustration of (a) perturbation of conduction and valence bandedges due to strong charge-induced local fields and (b) bandgap narrowing in the case of heavy doping. Note that the perturbation of the bandedges causes an effective *spatial* separation of electrons and *holes*, thereby changing carrier lifetimes.

Carrier Dynamics

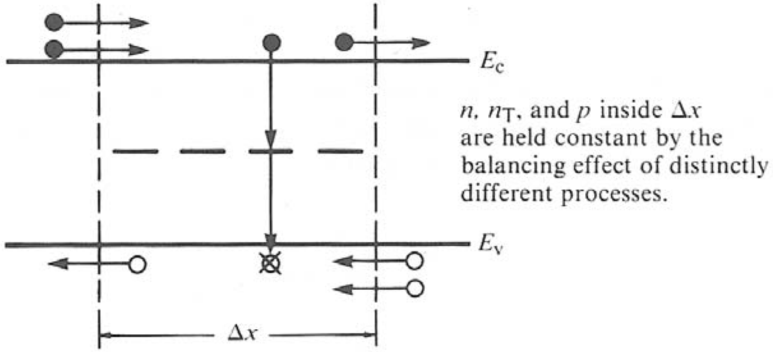
- Equilibrium
  - The static situation is maintained by the self-balancing of each fundamental process and its inverse. *G = R = 0*
- Steady-State
  - The condition is maintained by a trade-off between processes

  $G = R \neq 0$



Each circled pair of processes self-balances.

(a) Equilibrium



n, n_T, and p inside Δx are held constant by the balancing effect of distinctly different processes.

(b) Steady-state

Quasi-Fermi Level

In a semiconductor in equilibrium (i.e., without any incident photons or injection of electrons), the carrier densities can be calculated from an equilibrium Fermi level by using Fermi-Dirac or Boltzmann statistics outlined in Sec. 2.5.3. When excess carriers are created by one of the techniques described above, nonequilibrium conditions are generated and the concept of a Fermi level is no longer valid. One can, however, define nonequilibrium distribution functions for electrons and holes as

May not be steady-state

$$f_n(\mathcal{E}) = \frac{1}{1 + \exp\left(\frac{\mathcal{E} - \mathcal{E}_{fn}}{k_B T}\right)} \tag{3.1}$$

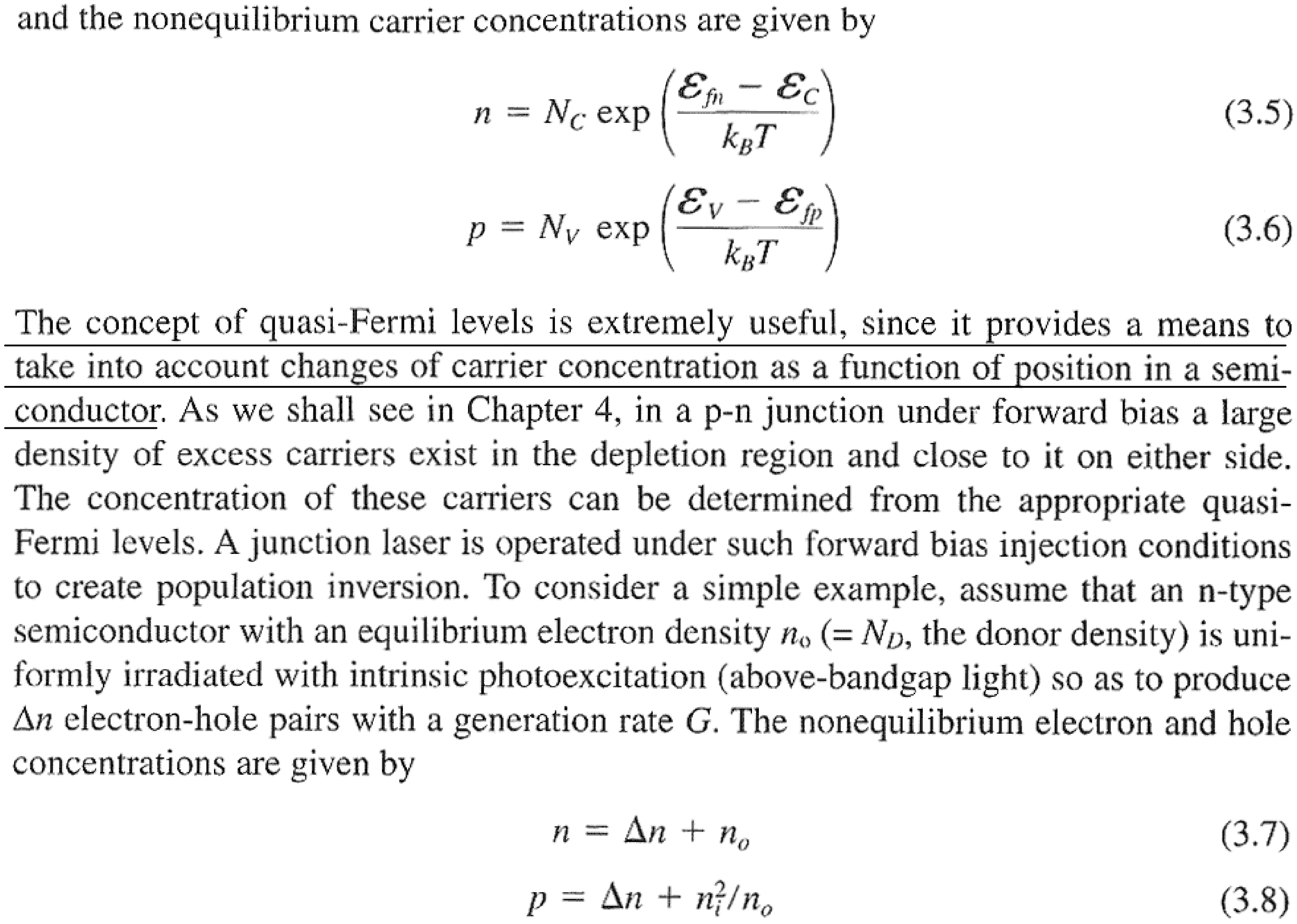
$$1 - f_p(\mathcal{E}) = \frac{1}{1 + \exp\left(\frac{\mathcal{E} - \mathcal{E}_{fp}}{k_B T}\right)} \tag{3.2}$$

These distribution functions define $\mathcal{E}_{fn}$ and $\mathcal{E}_{fp}$, the *quasi-Fermi levels* for electrons and holes, respectively. In some texts they are referred to as IMREFs (Fermi spelled backward). When the excitation source creating excess carriers is removed, $\mathcal{E}_{fn} = \mathcal{E}_{fp} = \mathcal{E}_F$. The difference $(\mathcal{E}_{fn} - \mathcal{E}_{fp})$ is a measure of the deviation from equilibrium. As with equilibrium statistics, we obtain for the nondegenerate case

$$f_n(\mathcal{E}) \cong \exp\left(\frac{\mathcal{E}_{fn} - \mathcal{E}}{k_B T}\right) \tag{3.3}$$

$$f_p(\mathcal{E}) \cong \exp\left(\frac{\mathcal{E} - \mathcal{E}_{fp}}{k_B T}\right) \tag{3.4}$$

Con’t



and the nonequilibrium carrier concentrations are given by

$$n = N_C \exp\left(\frac{\mathcal{E}_{fn} - \mathcal{E}_C}{k_B T}\right) \tag{3.5}$$

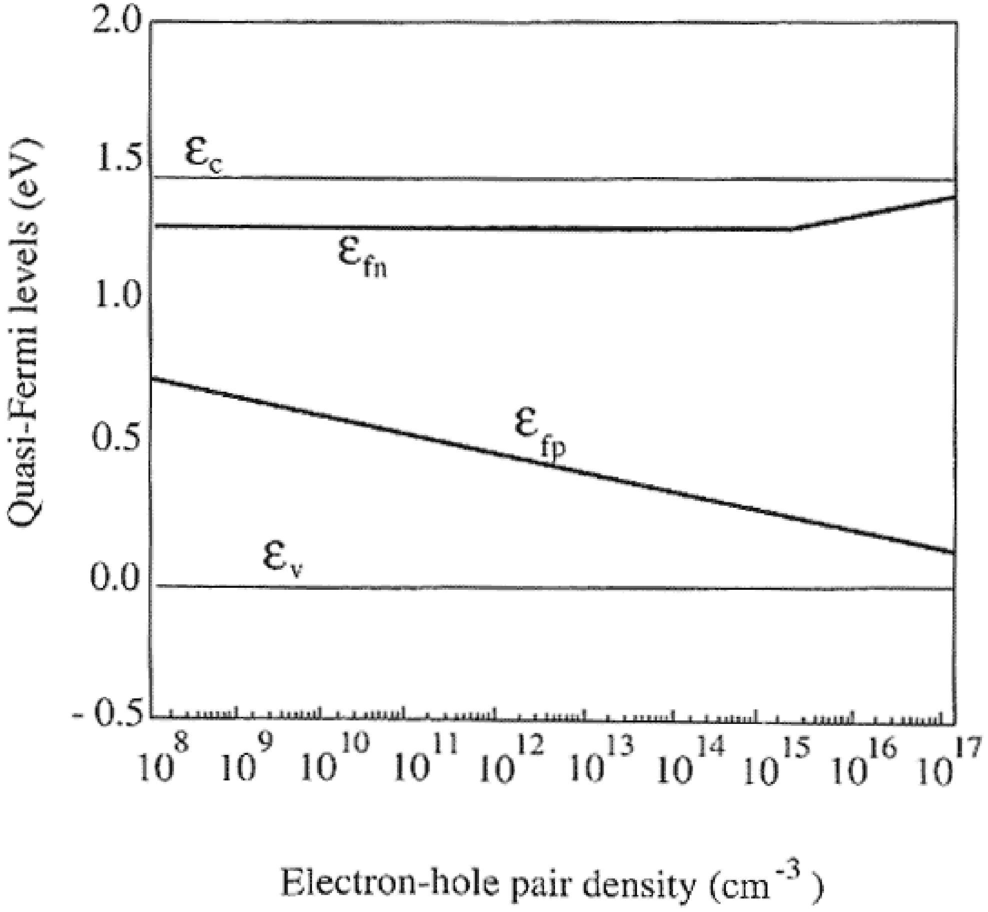
$$p = N_V \exp\left(\frac{\mathcal{E}_V - \mathcal{E}_{fp}}{k_B T}\right) \tag{3.6}$$

The concept of quasi-Fermi levels is extremely useful, since it provides a means to take into account changes of carrier concentration as a function of position in a semiconductor. As we shall see in Chapter 4, in a p-n junction under forward bias a large density of excess carriers exist in the depletion region and close to it on either side. The concentration of these carriers can be determined from the appropriate quasi-Fermi levels. A junction laser is operated under such forward bias injection conditions to create population inversion. To consider a simple example, assume that an n-type semiconductor with an equilibrium electron density n_o ($= N_D$, the donor density) is uniformly irradiated with intrinsic photoexcitation (above-bandgap light) so as to produce Δn electron-hole pairs with a generation rate G. The nonequilibrium electron and hole concentrations are given by

$$n = \Delta n + n_o \tag{3.7}$$

$$p = \Delta n + n_i^2/n_o \tag{3.8}$$

Cont’



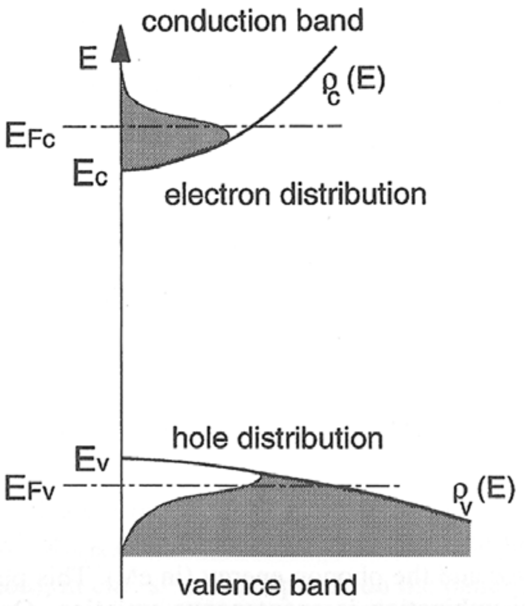


Figure 3.1 Energy position of the electron and hole quasi-Fermi levels as a function of pair density in GaAs at room temperature. It is assumed that the sample is n-type with $N_D = 10^{15}\,\text{cm}^{-3}$ (from M. Shur, *Physics of Semiconductor Devices*, © 1990. Reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey).

Optical Processes

Light Emission and Absorption

Terms

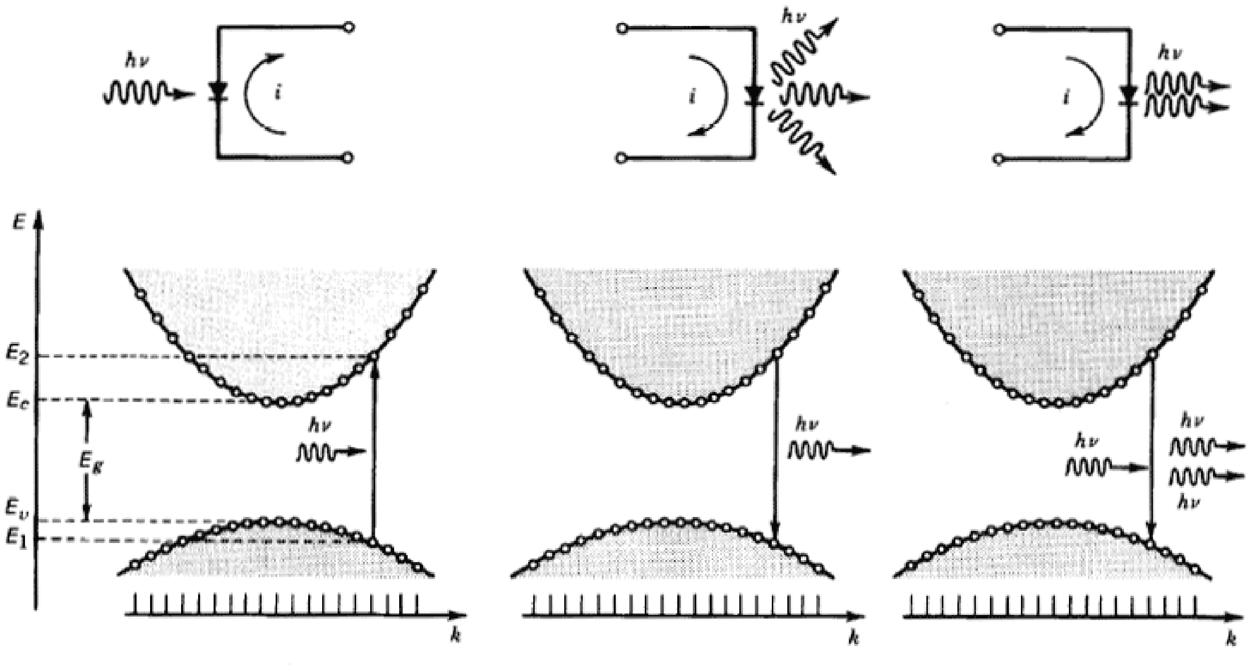
- Generation
- Recombination

Carrier process

- Emission
- Absorption

Photon process

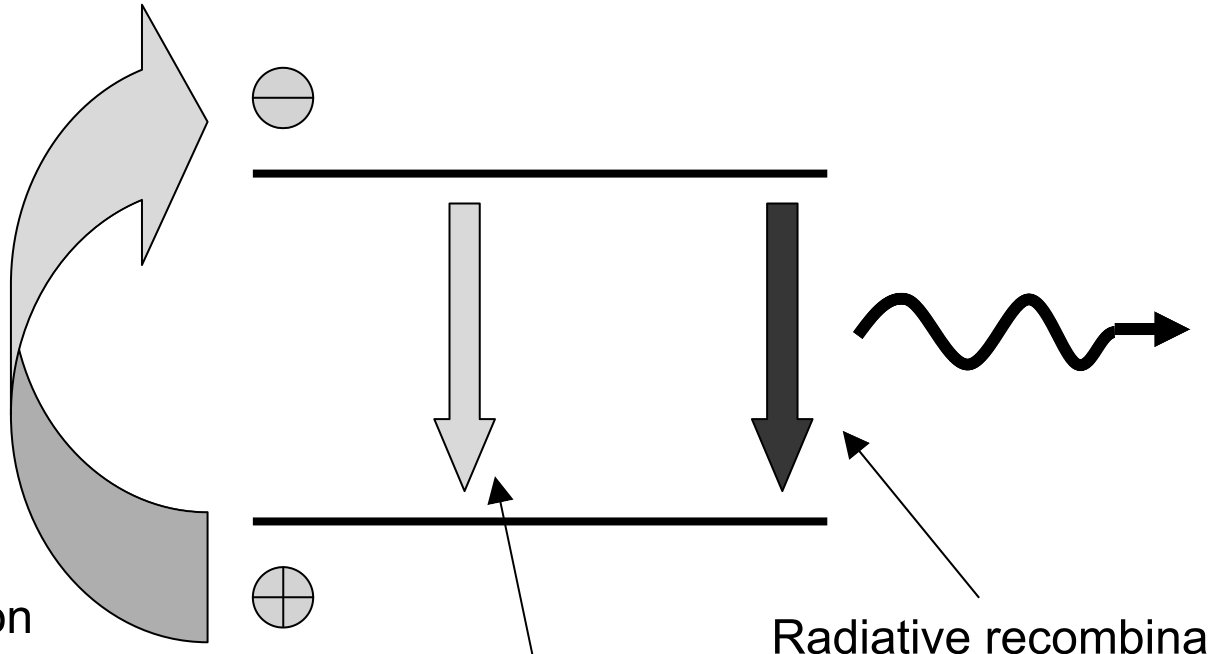
Basic Optical Processes for Light Emitting Devices



(a) (b) (c)

Figure 15.2-5 (*a*) The absorption of a photon results in the generation of an electron–hole pair. This process is used in the photodetection of light. (*b*) The recombination of an electron–hole pair results in the spontaneous emission of a photon. Light-emitting diodes (LEDs) operate on this basis. (*c*) Electron–hole recombination can be stimulated by a photon. The result is the induced emission of an identical photon. This is the underlying process responsible for the operation of semiconductor injection lasers.

Generation & Recombination



Generation
- Light pumping
- Carrier injection
- Electron bombardment

Radiative recombination

Nonradiative recombination
- Energy wasted by generating phonon (heat)

What is a Phonon?

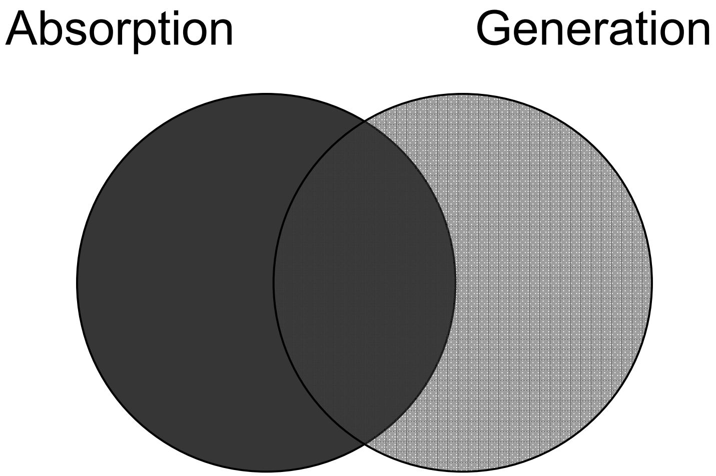
- Originated from crystal vibration
  - Could be transverse or longitudinal elastic wave
- Wave in crystal
  - Derive band structure (dispersion curve) for phonons
- By wave-particle duality, a wave in crystal can be envisioned as a particle (phonon)
- The energy of a lattice vibration is quantized, like that of a photon.

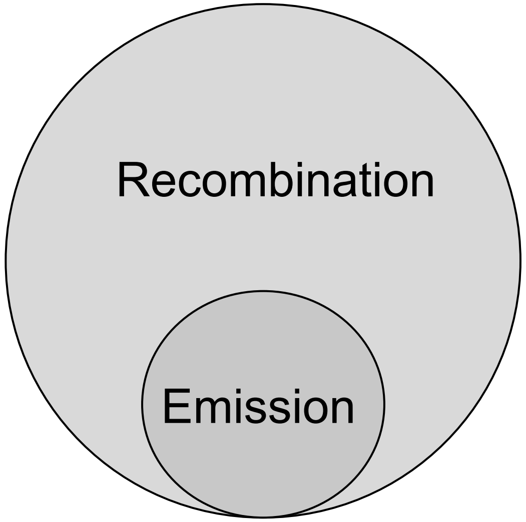
Classification of Recombinations

- In terms of light emission
  - Radiative recombination
  - Non-radiative recombination
- In terms of recombination path
  - Band to band recombination (radiative or non-radiative)
  - Deep level recombination (impurity or defect; nonradiative)
    - Bulk
    - Surface
  - Impurity recombination (nonradiative)
  - Auger recombination (nonradiative)
  - Exciton recombination (radiative)

Classifications of Absorption

- Band to Band Absorption (direct or indirect)
- Donor to Acceptor Absorption
- Impurity to Band Absorption
- Excitonic Absorption
- Low Energy Absorption
  - Impurity band
  - Intraband
  - Free carrier
- Electroabsorption
  - Franz-Keldysh
  - Stark Effect

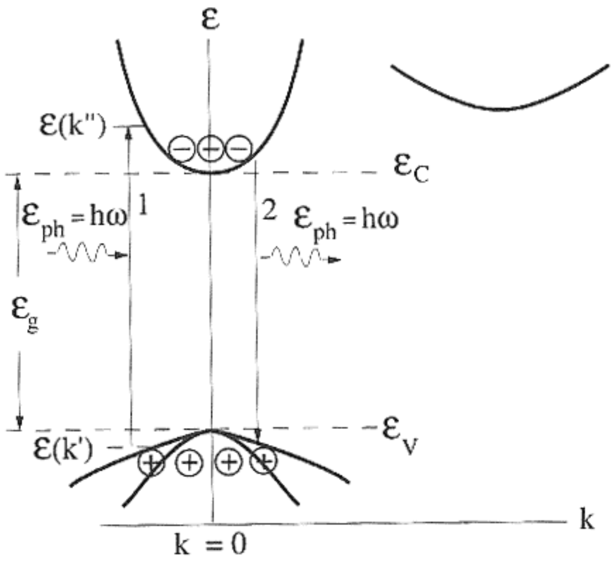

Absorption
Generation


Recombination
Emission

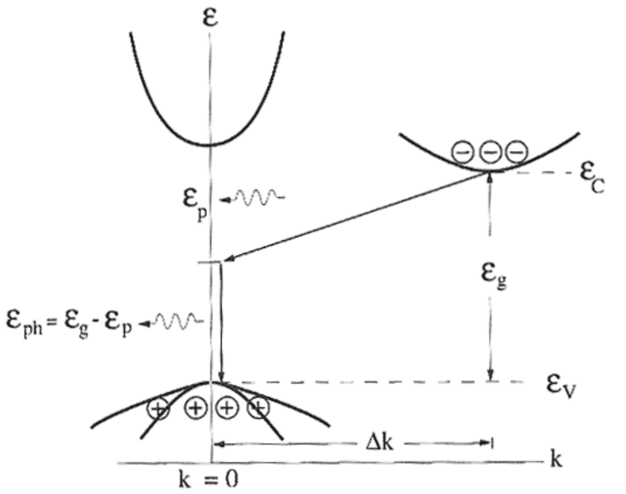
Optical Processes

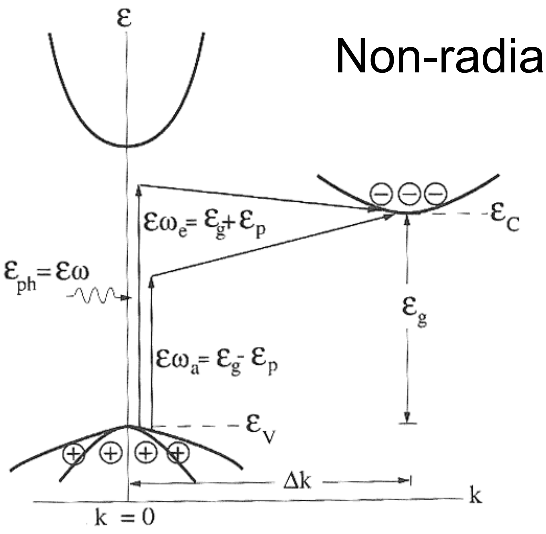
- Recombinations
- Absorptions
- Emission

Band to Band Recombination



Radiative





Non-radiative

Defect Recombination

- Nonradiative recombination usually takes place via surface or bulk defects and traps.

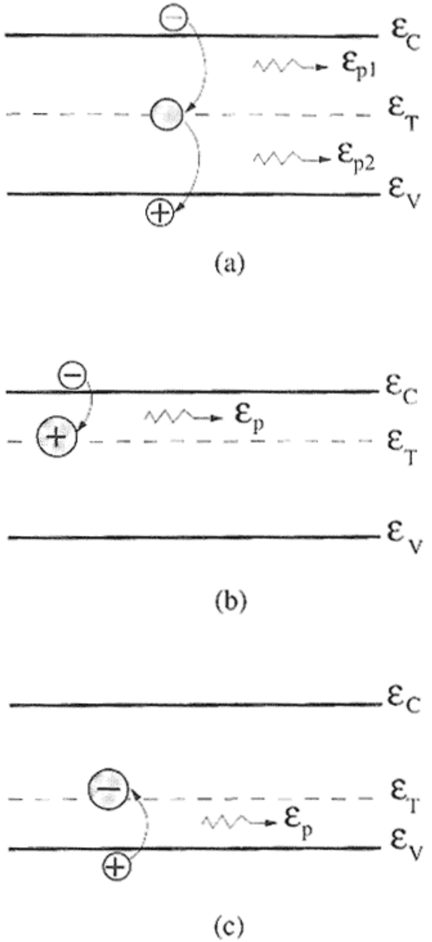


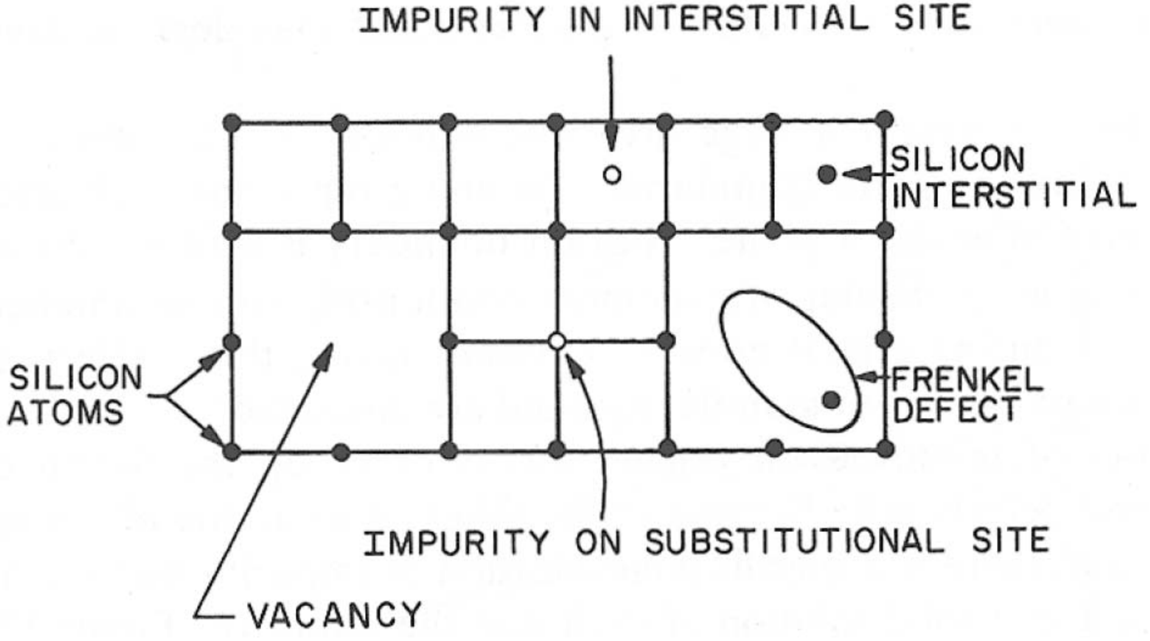
Figure 3.3 Nonradiative recombination at (a) recombination center, (b) electron trap, and (c) hole trap. The excess carrier energy in all cases is dissipated by single or multiple phonons.

Bulk Recombinations

- Steady state is produced by optical excitation or injection.
  - $\Delta n = \Delta p$ is established in the crystal
  - This equality is necessary for the maintenance of overall charge neutrality
- When the excitation source is removed the density of carriers returned to the equilibrium values n_0 and p_0
- The decay of excess carriers usually follows an exponential law with respect to time ~ $\exp(-t/\tau)$, where τ is defined as the lifetime of excess carriers.
- The excess carriers decay by radiative and/or nonradiative recombination, in which the excess energy is dissipated by photons and phonons. The former is of importance for the operation of luminescent devices.

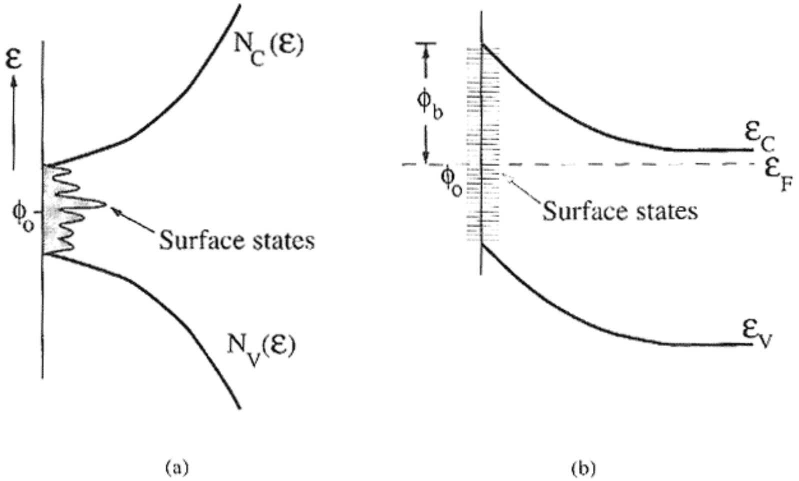
Deep Level Transitions

- Deep levels in the forbidden energy gap of semiconductors essentially act as carrier recombination or trapping center and adversely affect device performance.
- Native defects in the lattice, such as vacancies, interstitial or substitutional impurities of impurity-vacancy complexes can give rise to deep levels in semiconductors.



Surface Recombination via Defects

- All bulk properties of a semiconductor come to an abrupt halt at a surface
- The surface usually consists of dangling bonds or bonds that are satisfied by atoms other than the host atoms in the bulk (oxygen)
- There is a distribution of defect states in the bandgap at the surface and the Fermi level is pinned by the overall charge state at the surface than by charge neutrality in the bulk.
- Due to large density of such surface states, there is an enhanced recombination at the surface of the semiconductor.
- When light falls on a surface, most of it can recombine at the surface even before reaching the bulk. This is extremely detrimental to the operation of most optoelectronic devices.



(a) (b)

Figure 2.29 (a) Distribution of surface states in the bandgap of a semiconductor and (b) band-bending caused by Fermi level pinning at the surface. Φ_0 is called the *neutral* level. In (b) the acceptor-like surface states are occupied with electrons above Φ_0 and the surface has a net negative charge, which balances the positive charge in the depletion layer of the n-type semiconductor.

Auger Recombinations

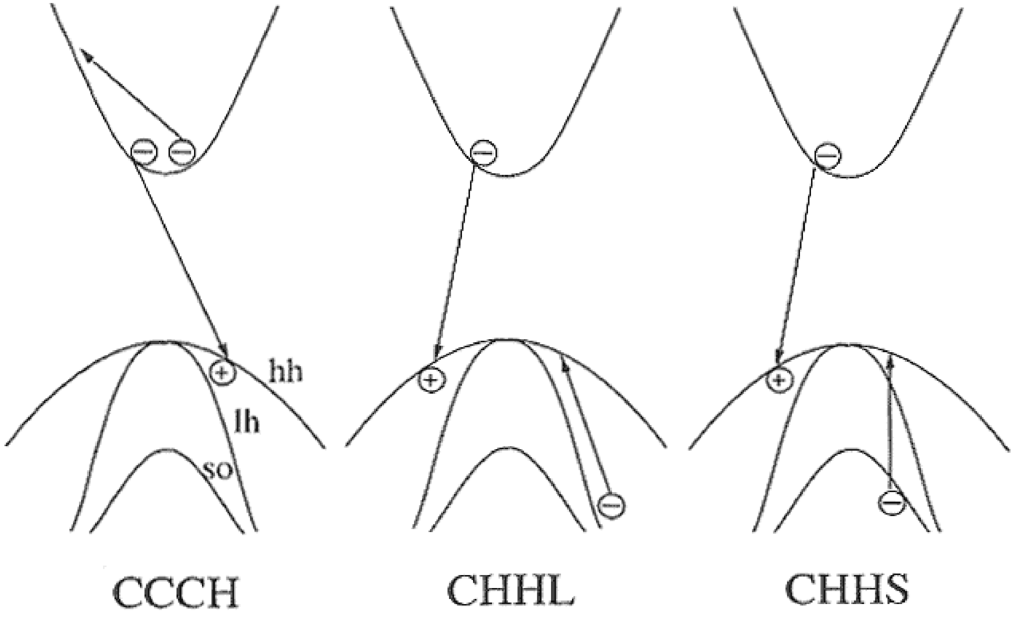
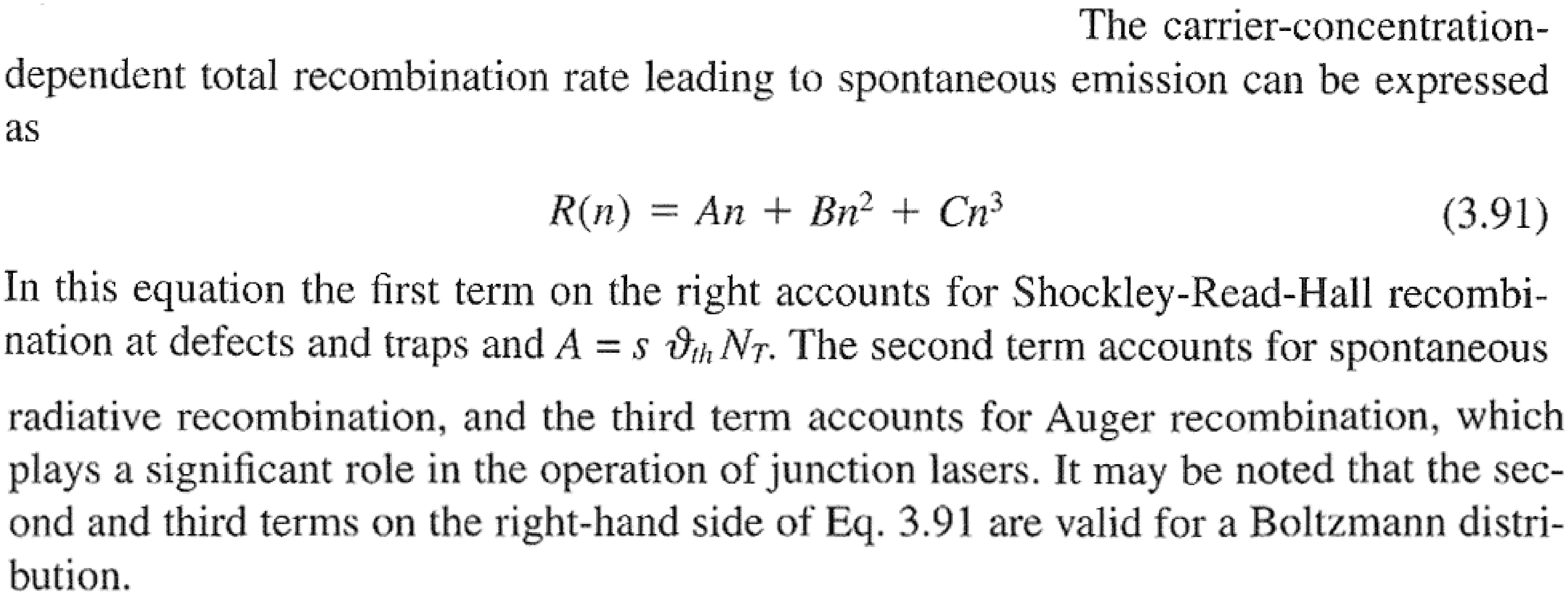


Figure 3.23 Different possible band-to-band Auger recombination processes in a direct bandgap semiconductor. Similar Auger transitions are also possible for impurity-band or D-A recombinations.

Total Spontaneous Recombination



The carrier-concentration-dependent total recombination rate leading to spontaneous emission can be expressed as

$$R(n) = An + Bn^2 + Cn^3 \tag{3.91}$$

In this equation the first term on the right accounts for Shockley-Read-Hall recombination at defects and traps and $A = s\ \vartheta_{th} N_T$. The second term accounts for spontaneous radiative recombination, and the third term accounts for Auger recombination, which plays a significant role in the operation of junction lasers. It may be noted that the second and third terms on the right-hand side of Eq. 3.91 are valid for a Boltzmann distribution.

Exciton

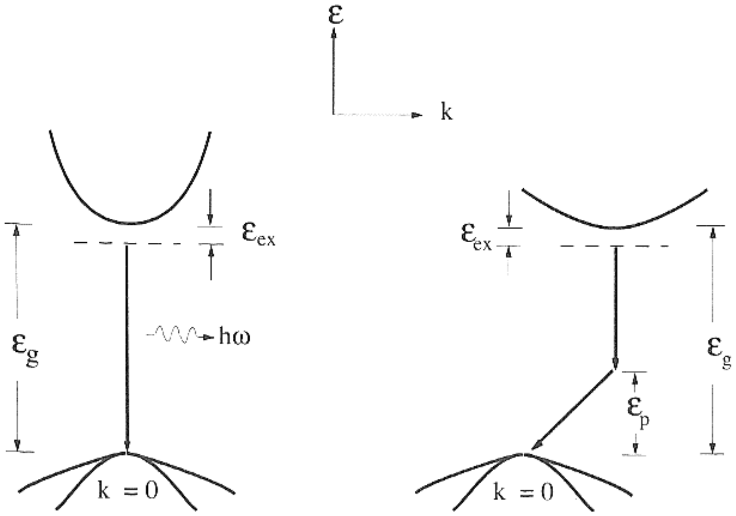
- Excitons are formed in very pure semiconductors at low temperature
- A pure material with unintentional doping is applied with an electrical field, then the impurities will be ionized and the additional charge modifies the bandedge potential.
- In addition, the ionized carriers screen the Coulomb interaction between the electrons and holes, thereby inhibiting or preventing the formation of excitons.

Exciton Recombination

3.6.3.1 Exciton Recombination. We have seen in Sec. 3.2.3 that electrons and holes produced by the absorption of a photon of near-bandgap energy can pair to form an exciton. Recombination of the electron-hole pair results in a narrow and sharp peak in the emission spectra. The energy of the emitted photon is

$$\hbar\omega = \mathcal{E}_g - \mathcal{E}_{ex} \tag{3.90}$$

where $\mathcal{E}_{ex}$ is quantized. In other words, in very pure crystals emission lines corresponding to the ground state and higher-order states may be seen. The process is shown in Fig. 3.19(a). In indirect bandgap semiconductors, a phonon needs to be involved, in the transition for momentum conservation, as shown in Fig. 3.19(b).



(a) (b)

Figure 3.19 Exciton recombination in (a) direct bandgap and (b) indirect bandgap semiconductor.

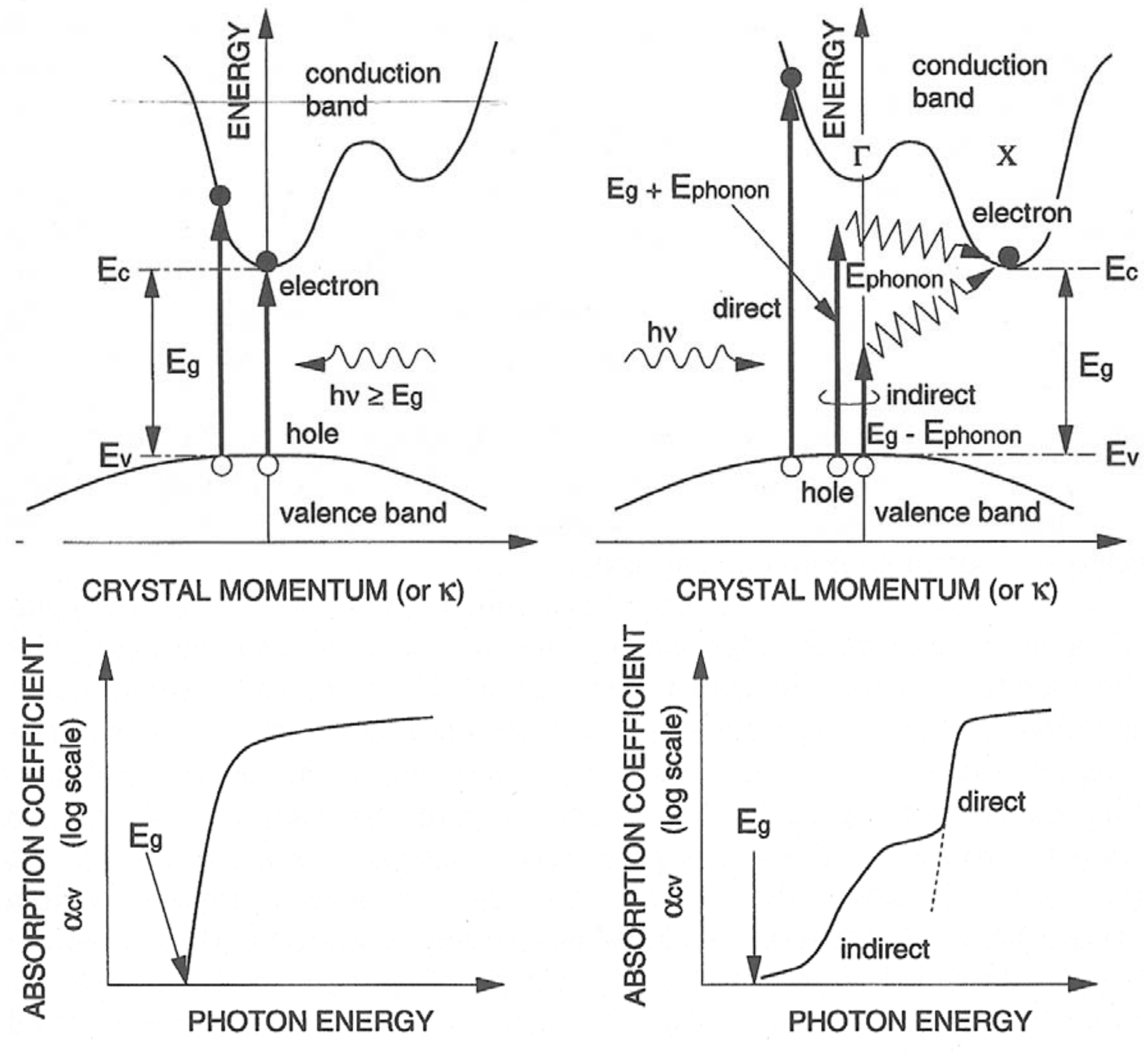
Exciton Recombination

- Free Exciton
- Bound Exciton
  - Free exciton couples with the impurity
  - The linewidth is ten times smaller
- We don’t see this effect in the inorganic light emitting devices

Optical Processes

- Recombinations
- Absorptions
- Emission

Direct and Indirect



(a) direct gap

(b) indirect gap

Exciton Absorption

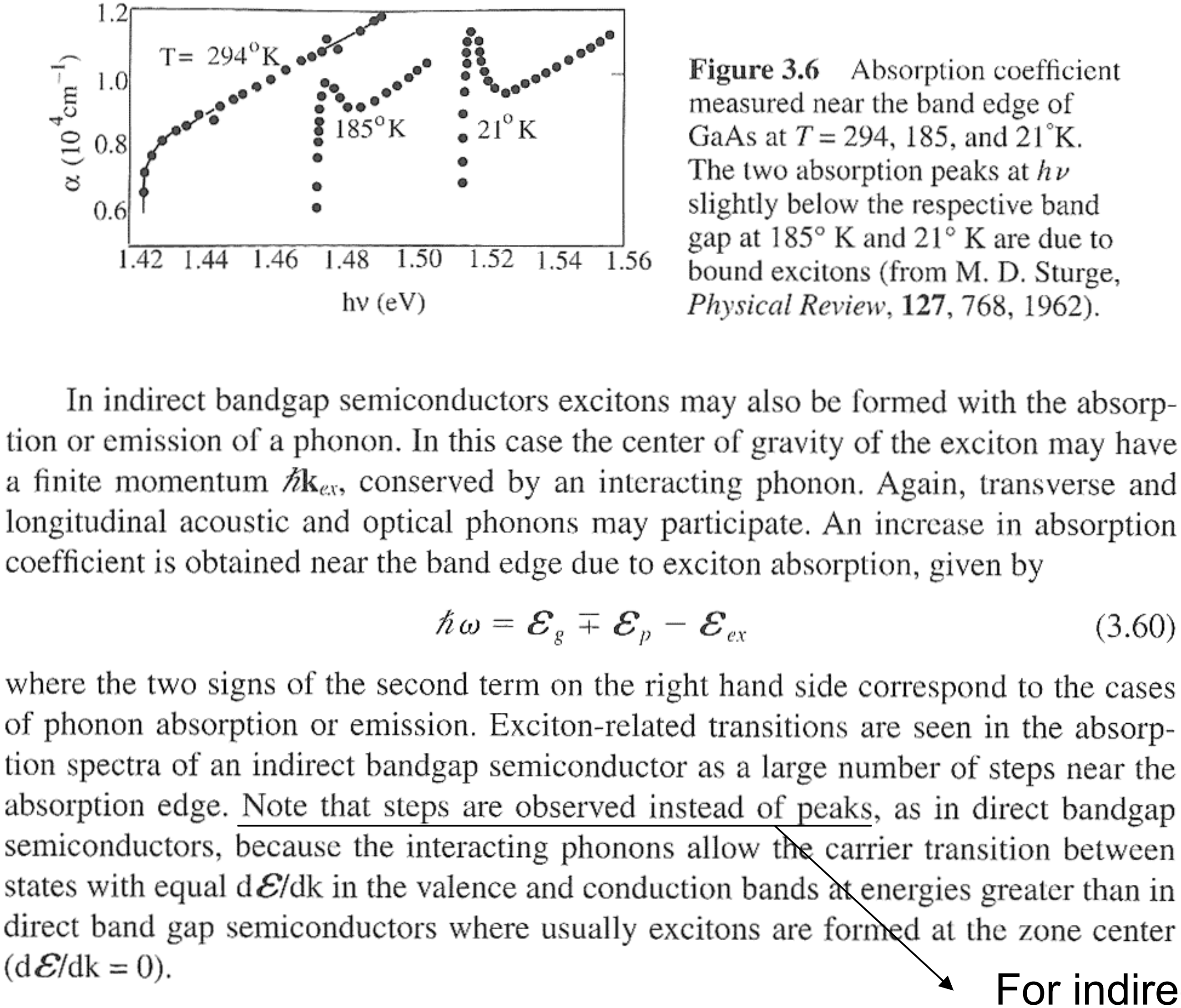


Figure 3.6 Absorption coefficient measured near the band edge of GaAs at $T = 294$, 185, and 21°K. The two absorption peaks at $h\nu$ slightly below the respective band gap at 185° K and 21° K are due to bound excitons (from M. D. Sturge, *Physical Review*, **127**, 768, 1962).

In indirect bandgap semiconductors excitons may also be formed with the absorption or emission of a phonon. In this case the center of gravity of the exciton may have a finite momentum $\hbar \mathbf{k}_{ex}$, conserved by an interacting phonon. Again, transverse and longitudinal acoustic and optical phonons may participate. An increase in absorption coefficient is obtained near the band edge due to exciton absorption, given by

$$\hbar\omega = \mathcal{E}_g \mp \mathcal{E}_p - \mathcal{E}_{ex} \qquad (3.60)$$

where the two signs of the second term on the right hand side correspond to the cases of phonon absorption or emission. Exciton-related transitions are seen in the absorption spectra of an indirect bandgap semiconductor as a large number of steps near the absorption edge. Note that steps are observed instead of peaks, as in direct bandgap semiconductors, because the interacting phonons allow the carrier transition between states with equal $d\mathcal{E}/dk$ in the valence and conduction bands at energies greater than in direct band gap semiconductors where usually excitons are formed at the zone center ($d\mathcal{E}/dk = 0$).

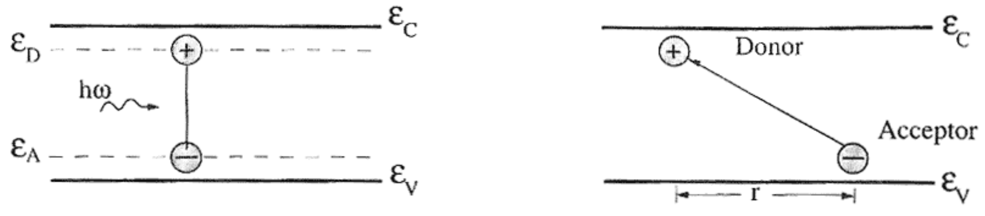
For indirect transition

Donor-Acceptor Absorption

Intentionally or unintentionally, both donors and acceptors are simultaneously present in a semiconductor, and any semiconductor is usually always compensated to some degree. Depending on the temperature and the state of occupancy of the impurity levels, it is possible to raise an electron from the acceptor to the donor level by absorbing a photon. This process is shown in Fig. 3.7. The energy of the photon absorbed is given by

$$\hbar\omega = \mathcal{E}_g - \mathcal{E}_D - \mathcal{E}_A + \frac{q^2}{\epsilon_0 \epsilon_r r} \tag{3.61}$$

where the last term on the right-hand side accounts for the Coulomb interaction between the donor and acceptor atoms in substitutional sites, which results in a lowering of their binding energies.



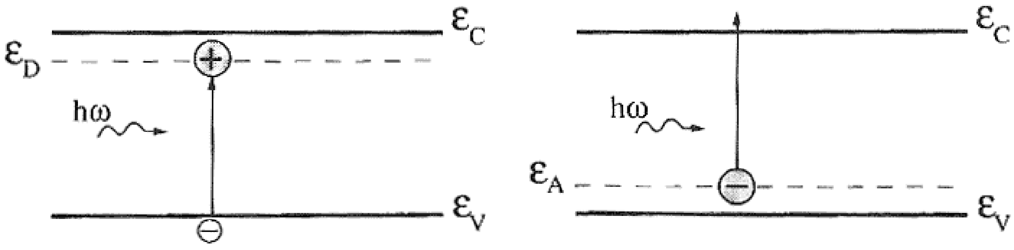
(a) (b)

Figure 3.7 Illustration of photon absorption due to a donor-acceptor transition. The separation between the impurity centers, *r*, is shown in (b).

The transitions are not always clearly identified because the resonances occur very close to the absorption edge

Impurity-Band Absorption

High-energy (near-bandgap) transitions can occur between ionized impurity levels and the opposite bandedge, as illustrated in Fig. 3.8. The photon energy absorbed is $\hbar\omega \cong \mathcal{E}_g - \mathcal{E}_b$, where $\mathcal{E}_b$ is the binding energy of the donor or acceptor level. It should be noted that the impurity levels need to be ionized. Since the transition occurs between a discrete impurity level and a band of energies, the transitions are observed as shoulders on the low-energy side of the absorption edge. In the emission spectra, these transitions are observed as peaks. As in a band-to-band transition, phonons need to be involved in impurity-band transitions in an indirect bandgap semiconductor for momentum conservation.



(a) (b)

Figure 3.8 Illustration of (a) donor-band and (b) acceptor-band absorption transitions.

Bandtailing

Degeneracy in semiconductors not only pushes the Fermi level into the band, but also results in a shrinkage of the bandgap. This effect is more commonly known as *bandtailing*, which results in an exponentially increasing absorption edge with photon energy as shown in Fig. 3.9 for GaAs.

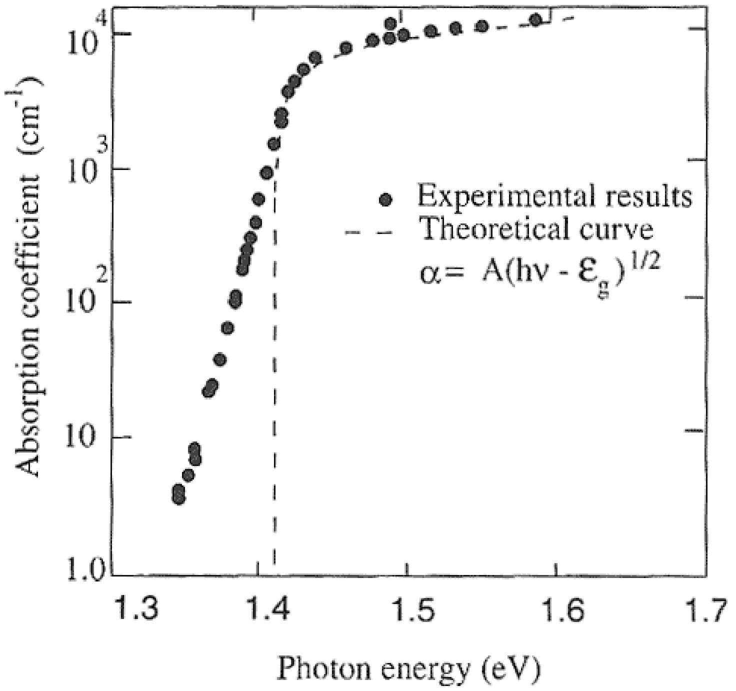


Figure 3.9 Absorption edge of GaAs at room temperature (from T. S. Moss, *Journal of Applied Physics*, **32**, 2136, 1961).

Low Energy Absorption

- Impurity-Band Transitions
- Intraband Transitions
- Free-Carrier Absorption

Effect of Electric Field on Absorption

Franz-Keldysh Effect

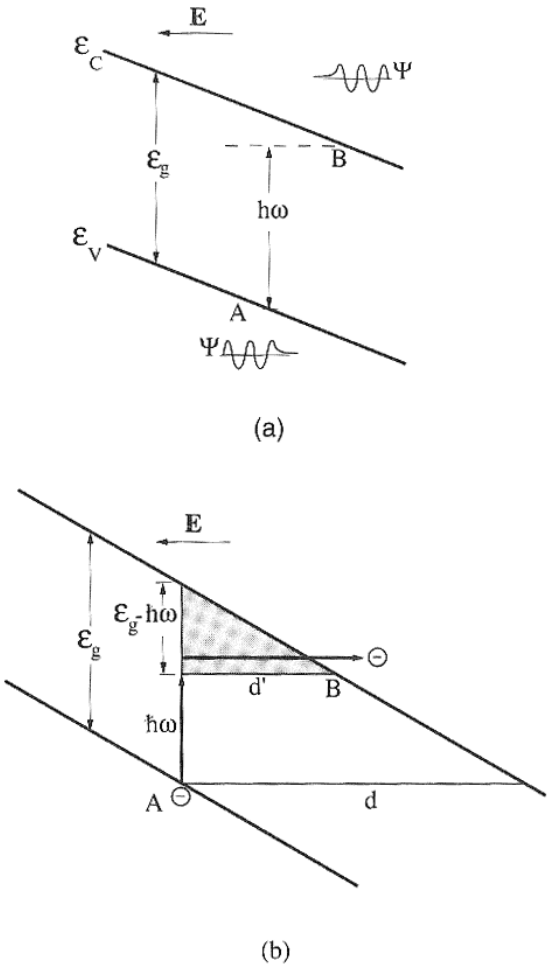


Figure 3.12 (a) I
due to an applied e
(b) absorption of p
$\hbar\omega < \mathcal{E}_g$ due to ca
(Franz-Keldysh ef

Quantum Confined Stark Effect

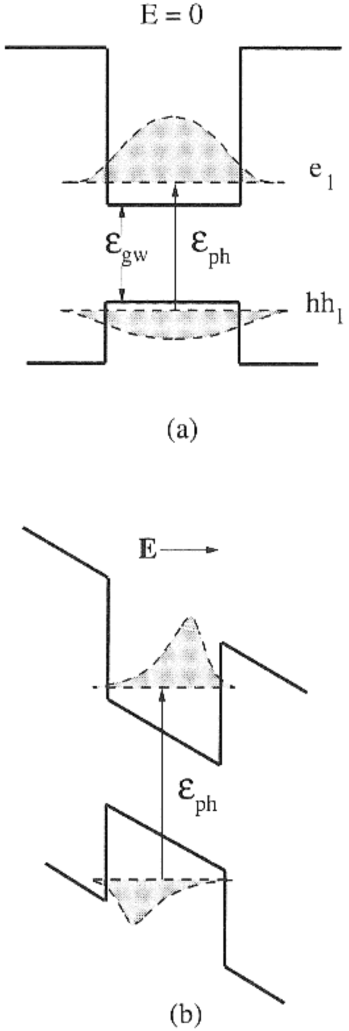


Figure 3.15 Absorption in a quantum well in the (a) absence and (b) presence of a transverse electric field.

Quantum-Confined Stark Effect

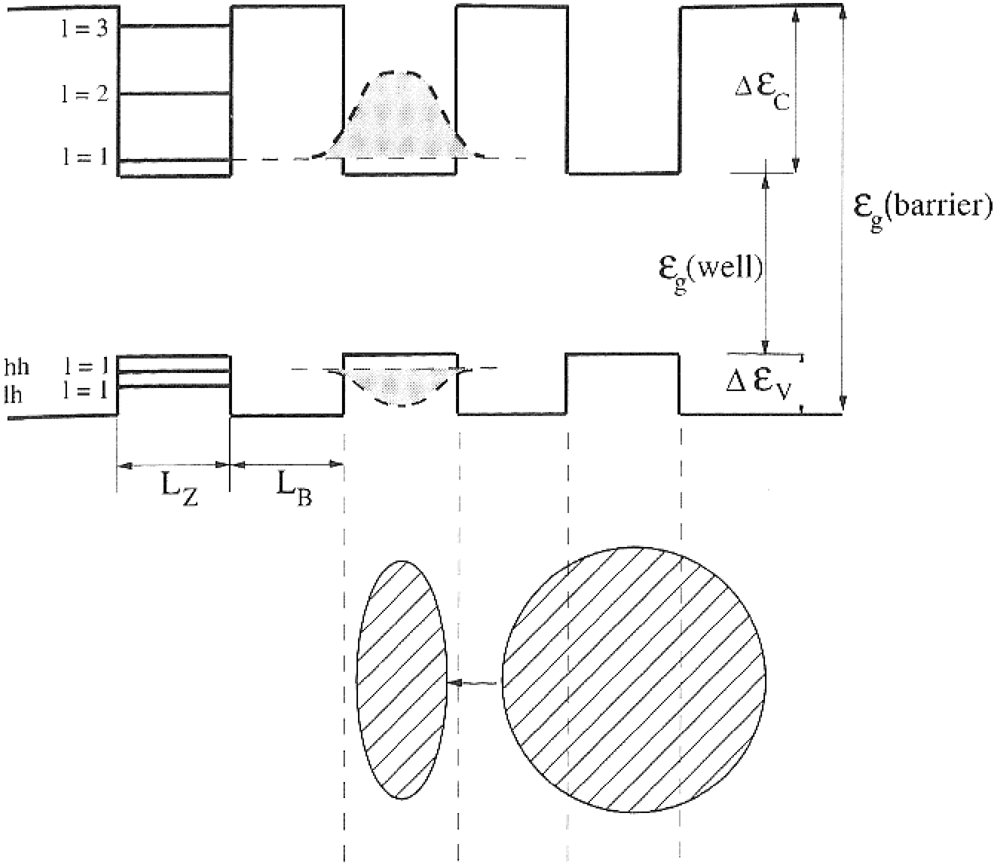


Figure 3.14 A typical multiquantum well and the compression of the bulk exciton in the well region.

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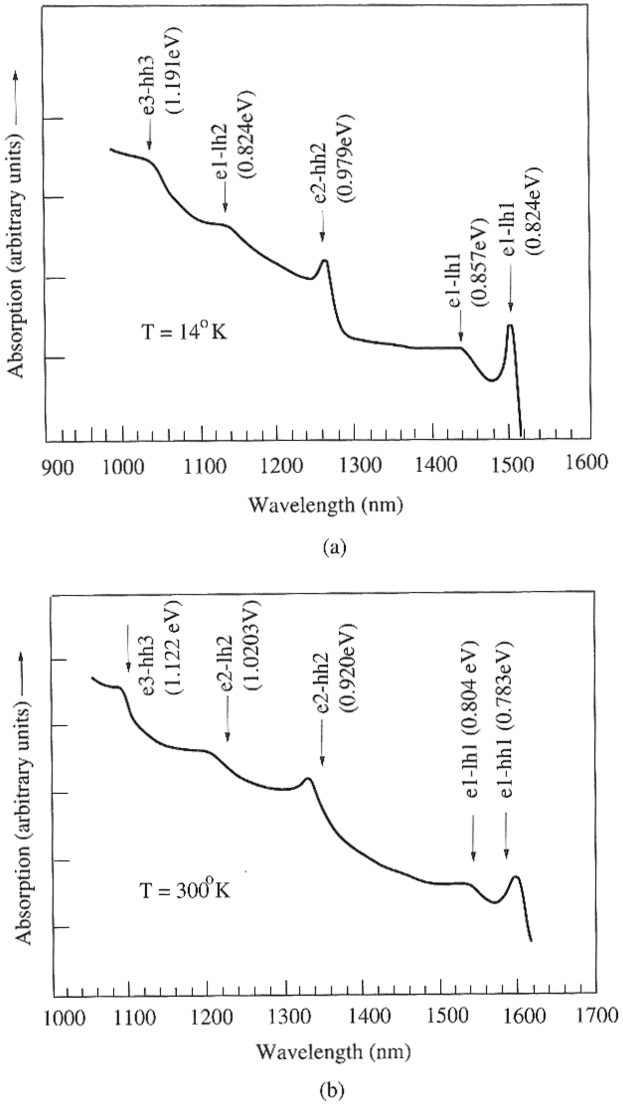
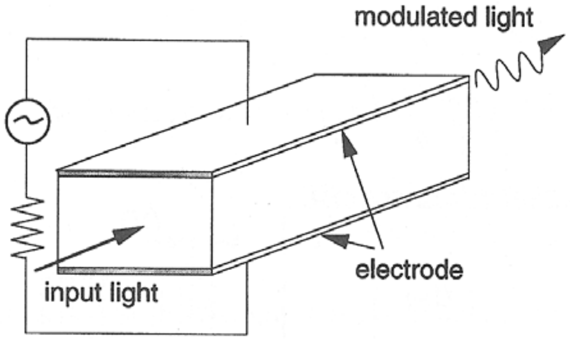


(a)

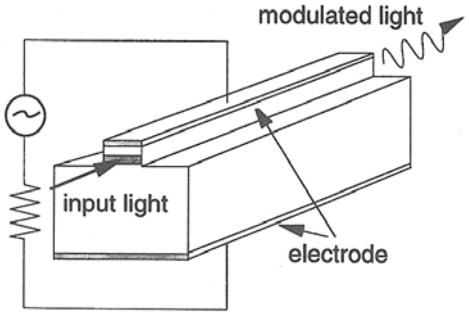
(b)

Figure 3.13 (a) Absorption spectrum of 40-period lattice-matched InGaAs/InAlAs MQW (measured by the author and co-workers) at 14°K; and (b) the calculated transitions based on a finite square well model at room temperature (from S. Gupta et al., *Journal of Applied Physics*, **69**, 3219, 1991).

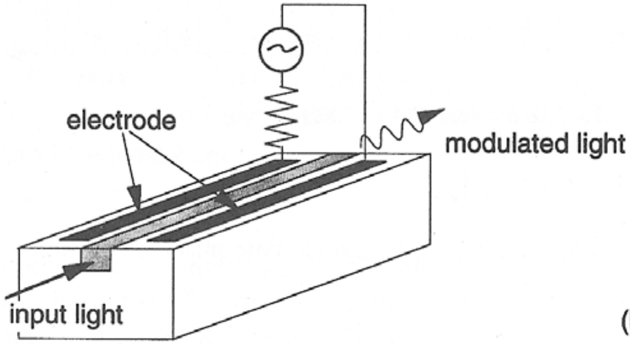
Electroabsorption Modulator



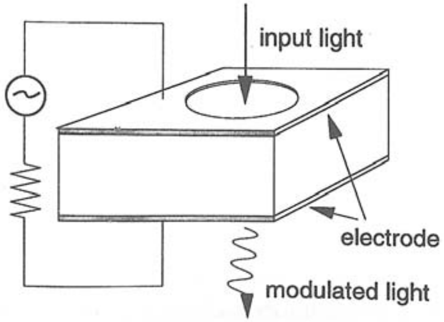
(a) bulk type



(c) waveguide type
(mesa structure)

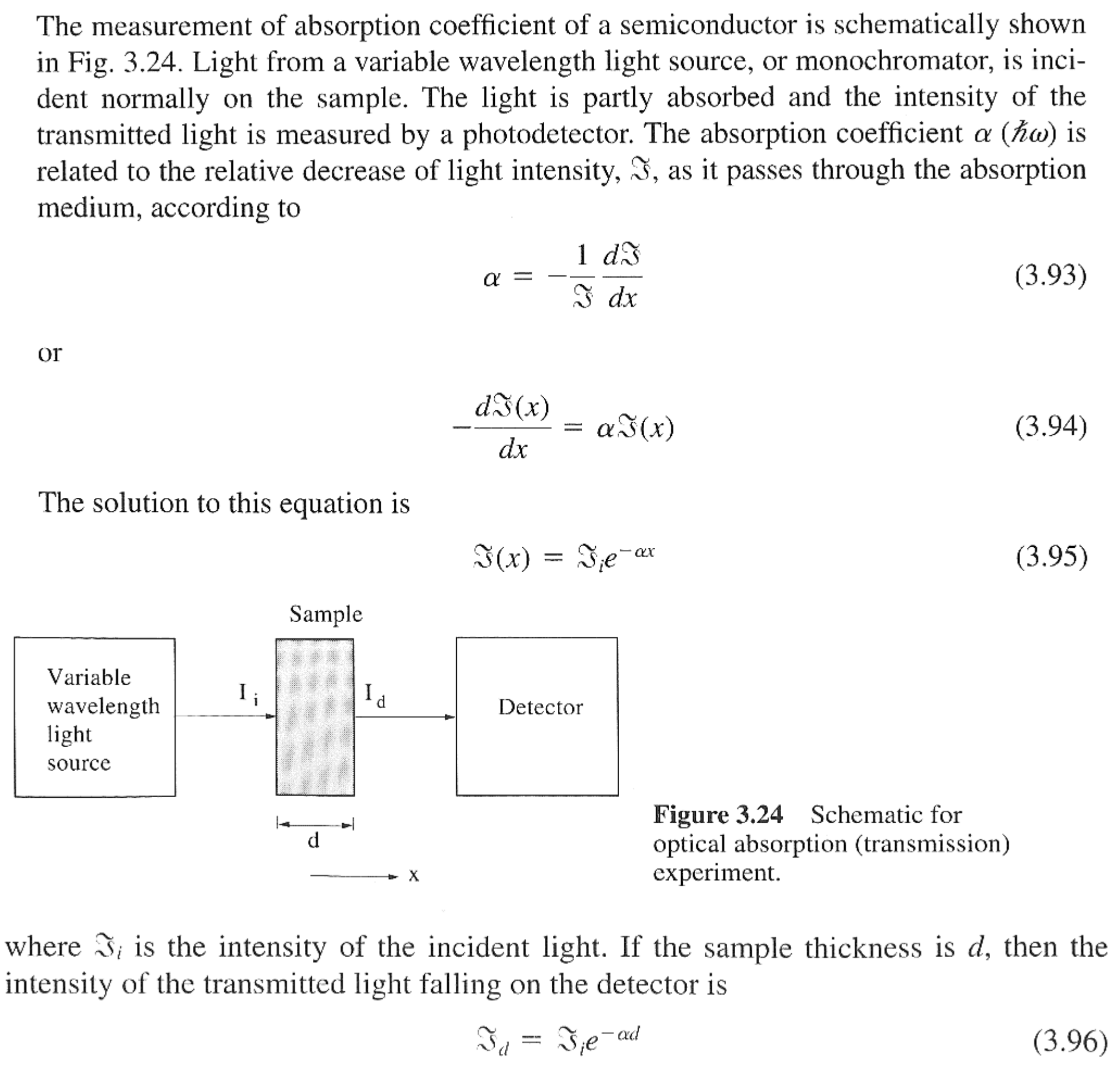


(b) waveguide type



(d) vertical-incidence type

Measurement of Absorption



The measurement of absorption coefficient of a semiconductor is schematically shown in Fig. 3.24. Light from a variable wavelength light source, or monochromator, is incident normally on the sample. The light is partly absorbed and the intensity of the transmitted light is measured by a photodetector. The absorption coefficient $\alpha\ (\hbar\omega)$ is related to the relative decrease of light intensity, $\Im$, as it passes through the absorption medium, according to

$$\alpha = -\frac{1}{\Im}\frac{d\Im}{dx} \tag{3.93}$$

or

$$-\frac{d\Im(x)}{dx} = \alpha\Im(x) \tag{3.94}$$

The solution to this equation is

$$\Im(x) = \Im_i e^{-\alpha x} \tag{3.95}$$

Figure 3.24 Schematic for optical absorption (transmission) experiment.

where $\Im_i$ is the intensity of the incident light. If the sample thickness is d, then the intensity of the transmitted light falling on the detector is

$$\Im_d = \Im_i e^{-\alpha d} \tag{3.96}$$

Absorption Spectra

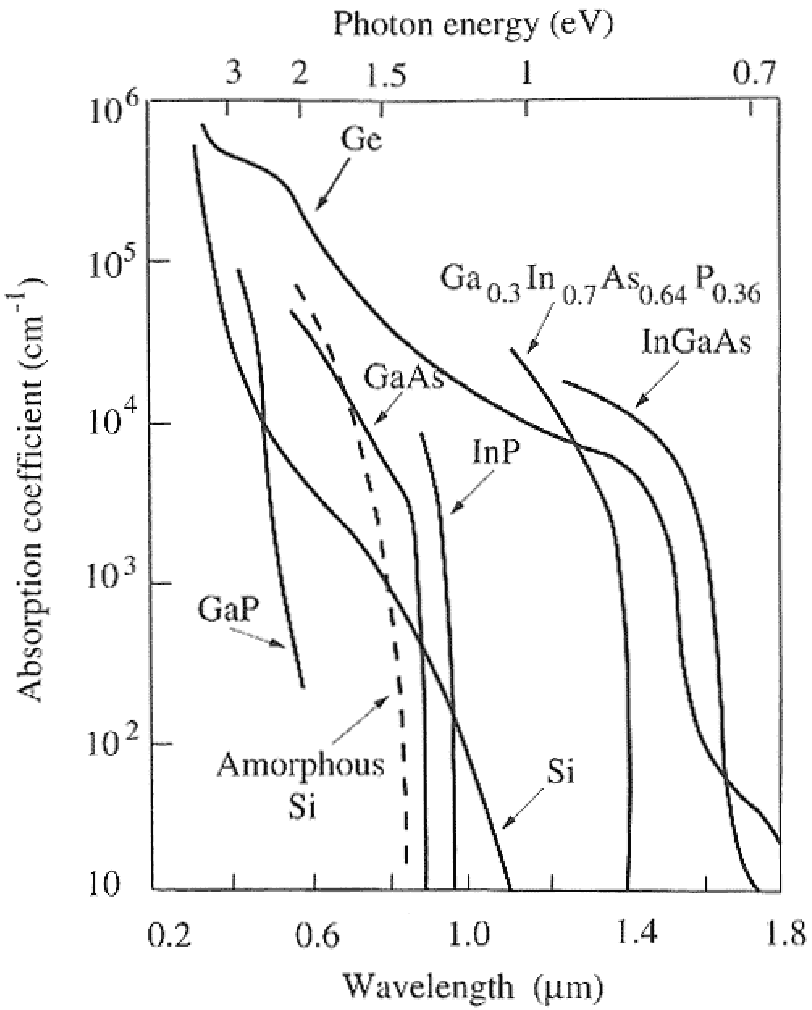
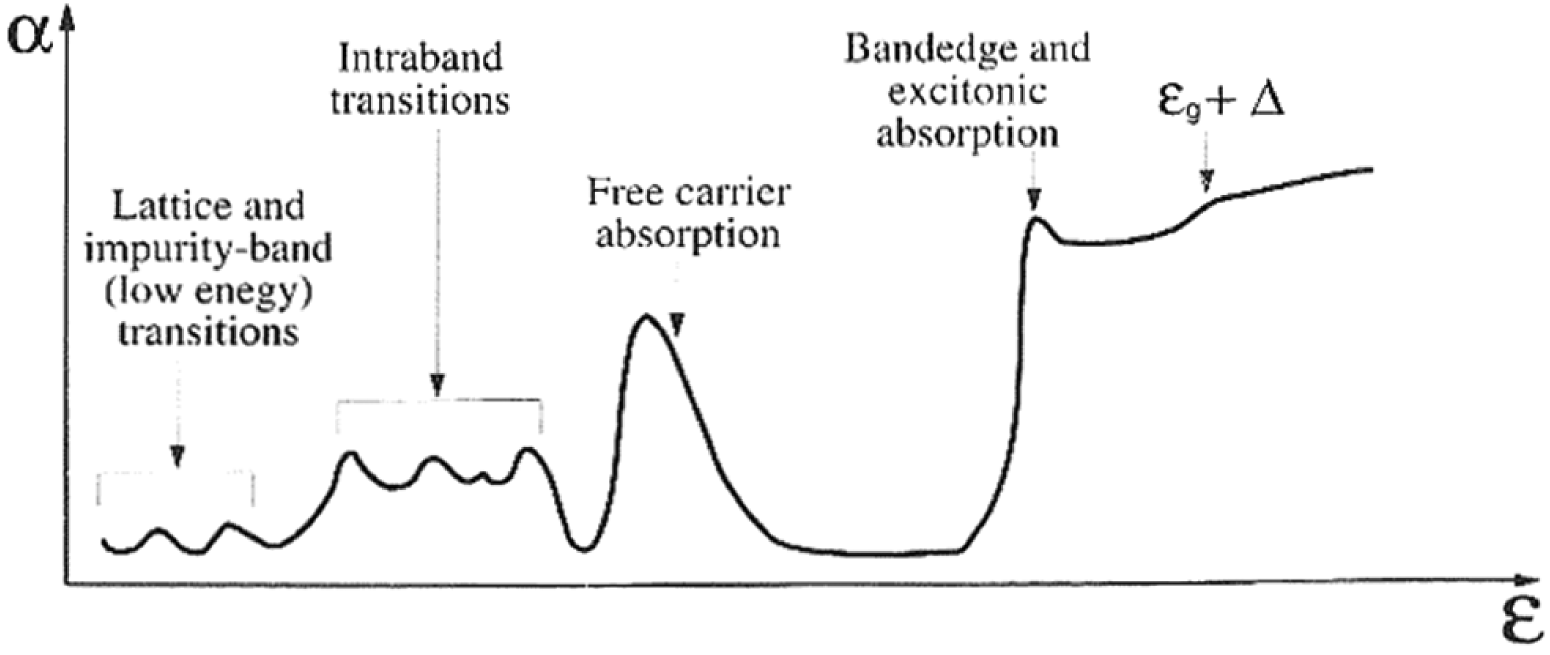
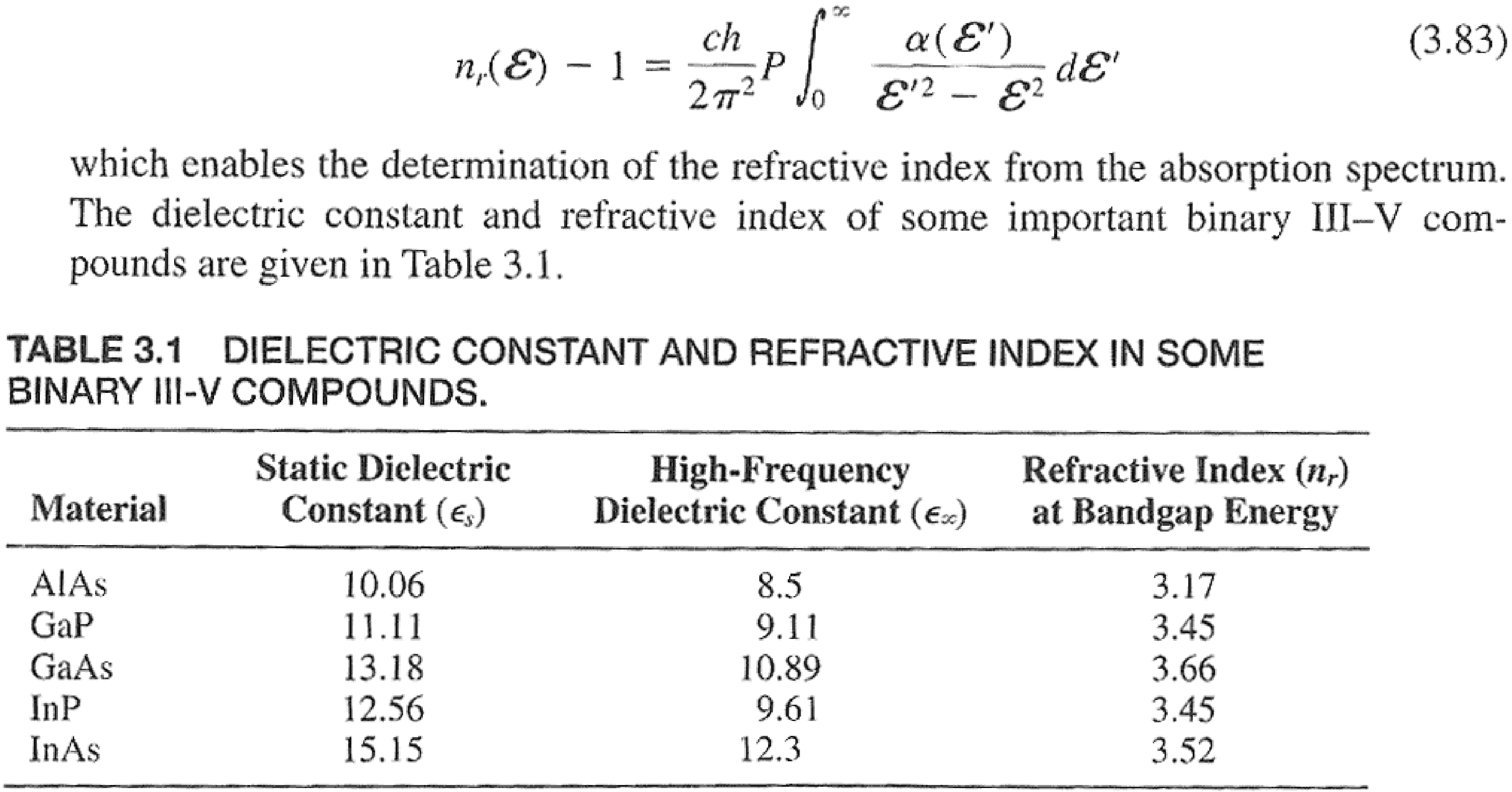


Figure 3.11 Near-bandgap absorption spectra of different semiconductors (from M. Shur, *Physics of Semiconductor Devices*, ©1990. Reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey).

Absorption Spectrum



Kramers-Kronig Relations



$$n_r(\mathcal{E}) - 1 = \frac{ch}{2\pi^2} P \int_0^{\infty} \frac{\alpha(\mathcal{E}')}{\mathcal{E}'^2 - \mathcal{E}^2} \, d\mathcal{E}' \qquad (3.83)$$

which enables the determination of the refractive index from the absorption spectrum. The dielectric constant and refractive index of some important binary III–V compounds are given in Table 3.1.

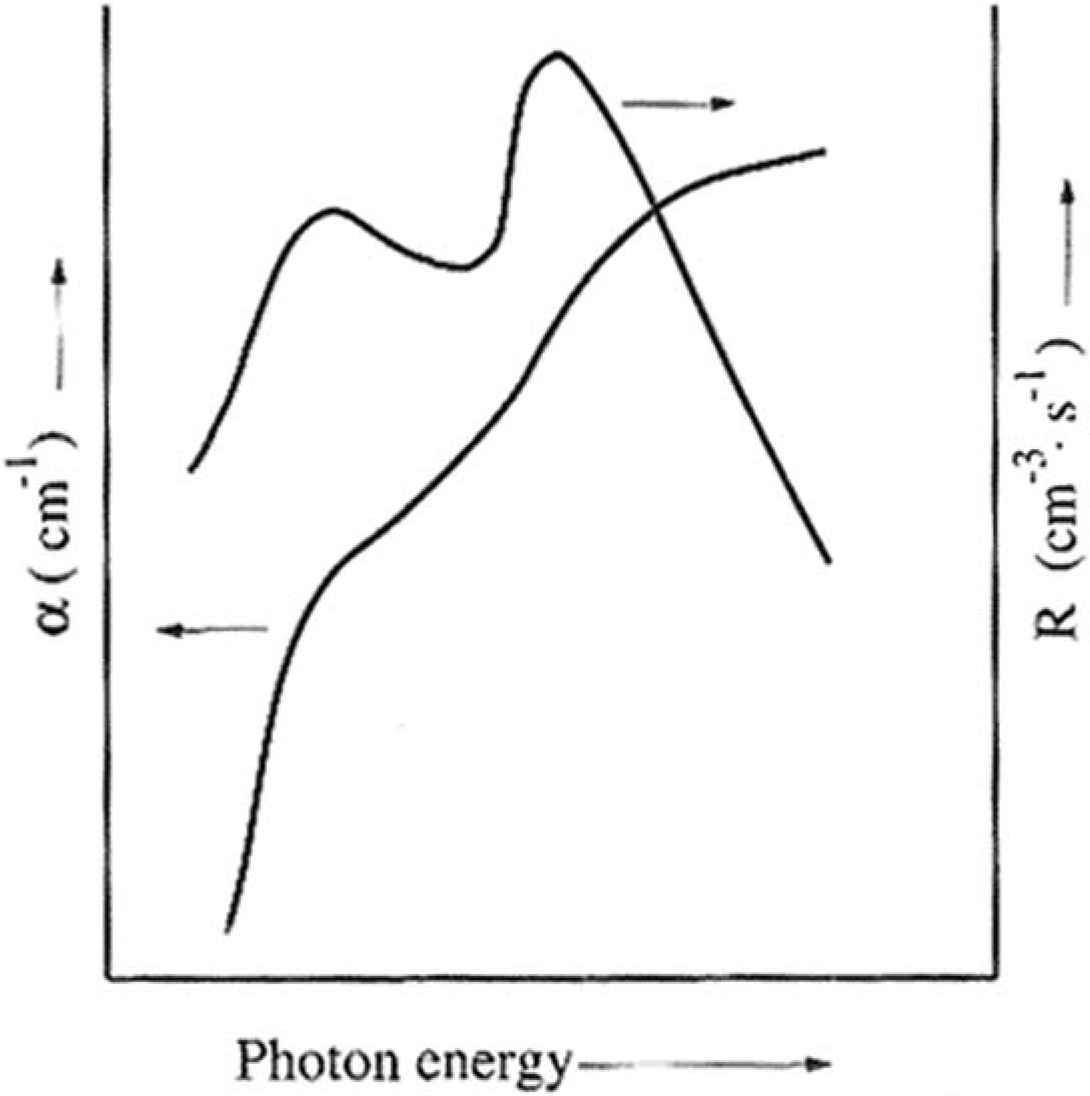
TABLE 3.1 DIELECTRIC CONSTANT AND REFRACTIVE INDEX IN SOME BINARY III-V COMPOUNDS.

Material	Static Dielectric Constant (ϵ_s)	High-Frequency Dielectric Constant (ϵ_∞)	Refractive Index (n_r) at Bandgap Energy
AlAs	10.06	8.5	3.17
GaP	11.11	9.11	3.45
GaAs	13.18	10.89	3.66
InP	12.56	9.61	3.45
InAs	15.15	12.3	3.52

Optical Processes

- Recombinations
- Absorptions
- Emission

Absorption and Emission Spectra



Band-to-Band Emission

- Conditions
  - Temperature of the sample is high enough so that $k_B T > E_{ex}$
  - There are sufficient number of free carriers in the sample producing local fields to dissociate the exciton
- The energy position of the emission peak depends on the temperature and intensity of excitation. (band filling effect)
- For light hole, density and transition probability is much lower so the transitions involving light holes are normally not seen in the spectra

DA, BA and DB Emission

- DA transition gives rise to a broad peak in the emission
- BA and DB can not be distinguished on the spectra because the binding energy are too close.
- DA transitions are 4 times higher than BA, DB transitions.

Quantum Well Luminescense

- Nonresonant excitation:
  - Excess electron-hole population is generally created in the barrier, from which they quickly diffuse and thermalize to the lowest bound states in the well region.

$$\hbar\omega \cong \mathcal{E}_{gw} + \mathcal{E}_{e1} + \mathcal{E}_{hh1}$$

- Resonant excitation:
  - Transitions between light hole bands and heavy hole bands can be seen.
- For well sizes of 100Å or less, the luminescent properties of the quantum well are determined by the quality of the well material, the perfection of the interface and the quality of the barrier material. The width (FWHM)of the luminescence spectrum can be analyzed to understand the optical quality of the quantum.

Photoluminescence Measurement

- Photoluminescence is the optical radiation emitted by a material resulting from its nonequlibrium state caused by an external light excitation.
- Three distinct processes take place to result in the light emission:
  - Absorption of exciting light and thus creation of electron-hole pairs
  - Partial radiative recombination of these electron-hole pairs
  - Escape of this radiation from the system

Cont’

- The highest concentration is near the illuminated surface of the sample, the resulting carrier distribution is both inhomogeneous and nonequlibrium
- To regain homogeneity and equilibrium, the excess carriers will diffuse away from the surface while recombining radiatively and nonradiatively.
- The emitted radiation is subject to self-absorption; thus it will not propagate far from the emission region.

Photoluminescence Setup

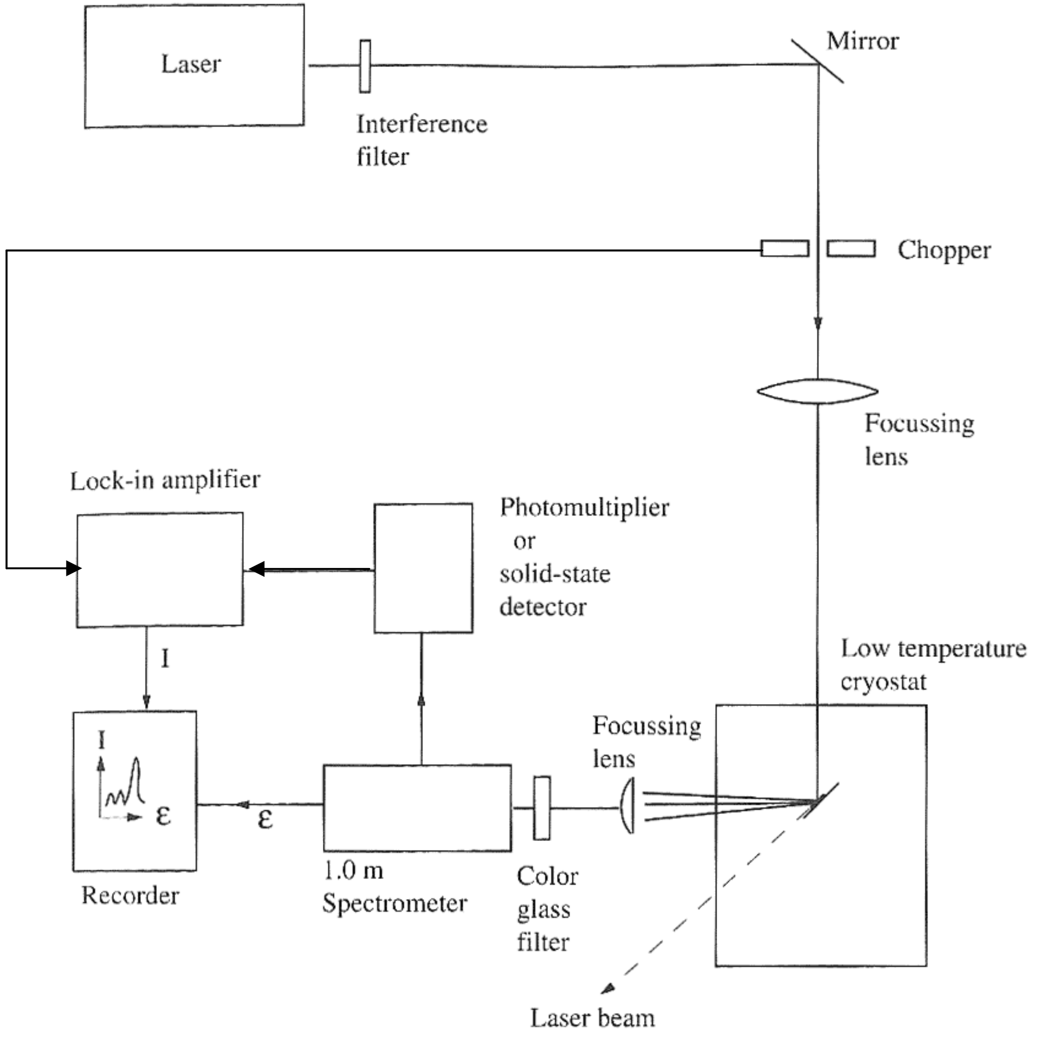


Figure 3.26 Photoluminescence measurement system.

Carrier Transport

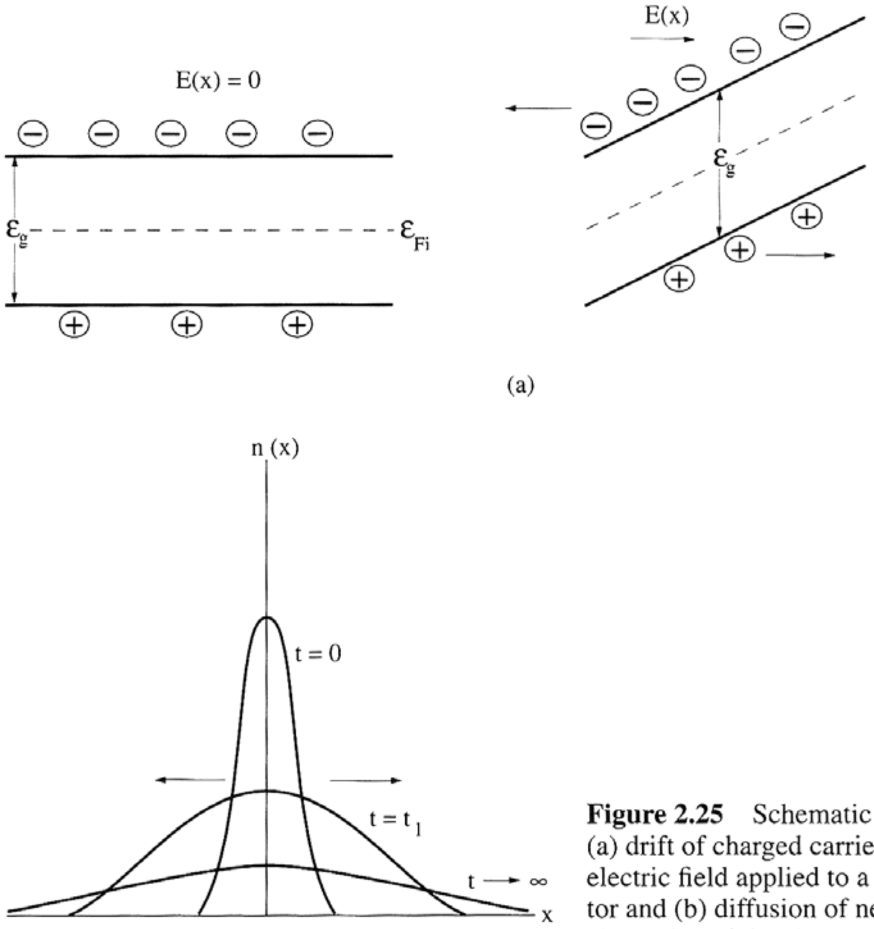
Conduction Process

- Requirements
  - A partially filled band; since a completely filled or a completely empty band will not conduct
    - Doping
    - Temperature
  - An external force; because the carriers have a scattering limited thermal velocity which is not directional without such force.

Directional Movement

- Drift
  - With external force, the electrons and holes move in the opposite directions.
- Diffusion
  - The carriers can acquire directional motion due to a concentration gradient

Cont’



(a)

(b)

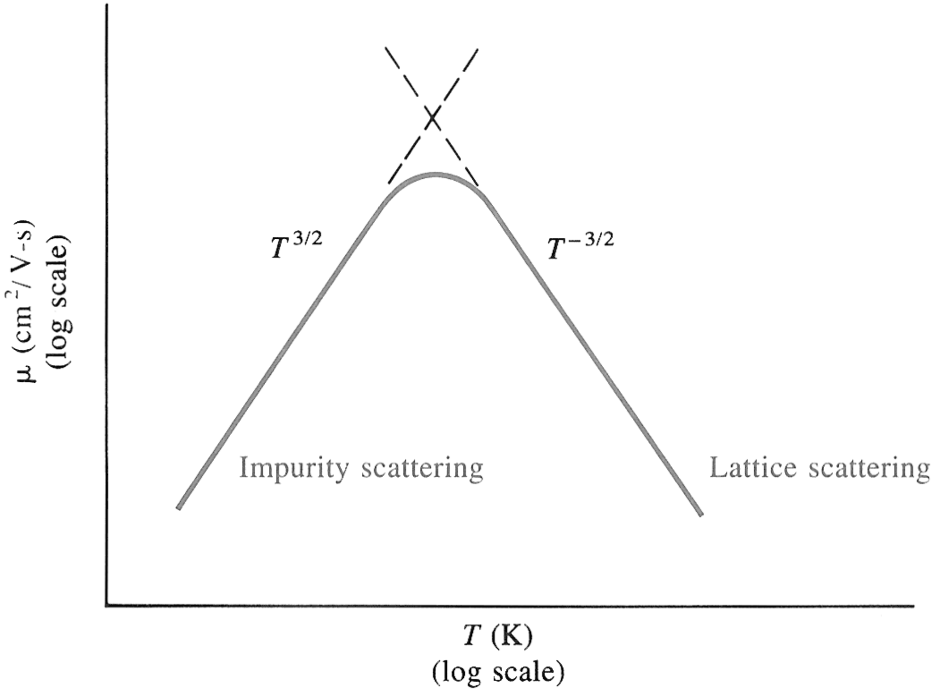
Figure 2.25 Schematic illustration of (a) drift of charged carriers due to an electric field applied to a semiconductor and (b) diffusion of neutral or charged particles due to a concentration gradient.

Drift

- Electron and holes drifting in their respective bands is similar to conduction in metals
  - – The carrier acceleration is frequently interrupted by scattering events, i.e. collisions between the carriers and ionized impurity atoms, thermally agitated lattice atoms or other scattering center
  - – Ohm's law $J_{dr} = -nq\mathcal{V} = \sigma E$
    - σ is the conductivity of the sample
    - E is the applied electric field
    - $\mathcal{V} = \mathcal{V}_D$ is the average scattering-limited drift velocity of the electron
  - – Carriers respond to thermal and external field at the same time, but thermal motion averages out to zero

Effects of Temperature on Mobility

- Frequency of lattice scattering increases as temperature increases
- Frequency of impurity scattering increases as temperature decrease



Effects of Doping on Mobility

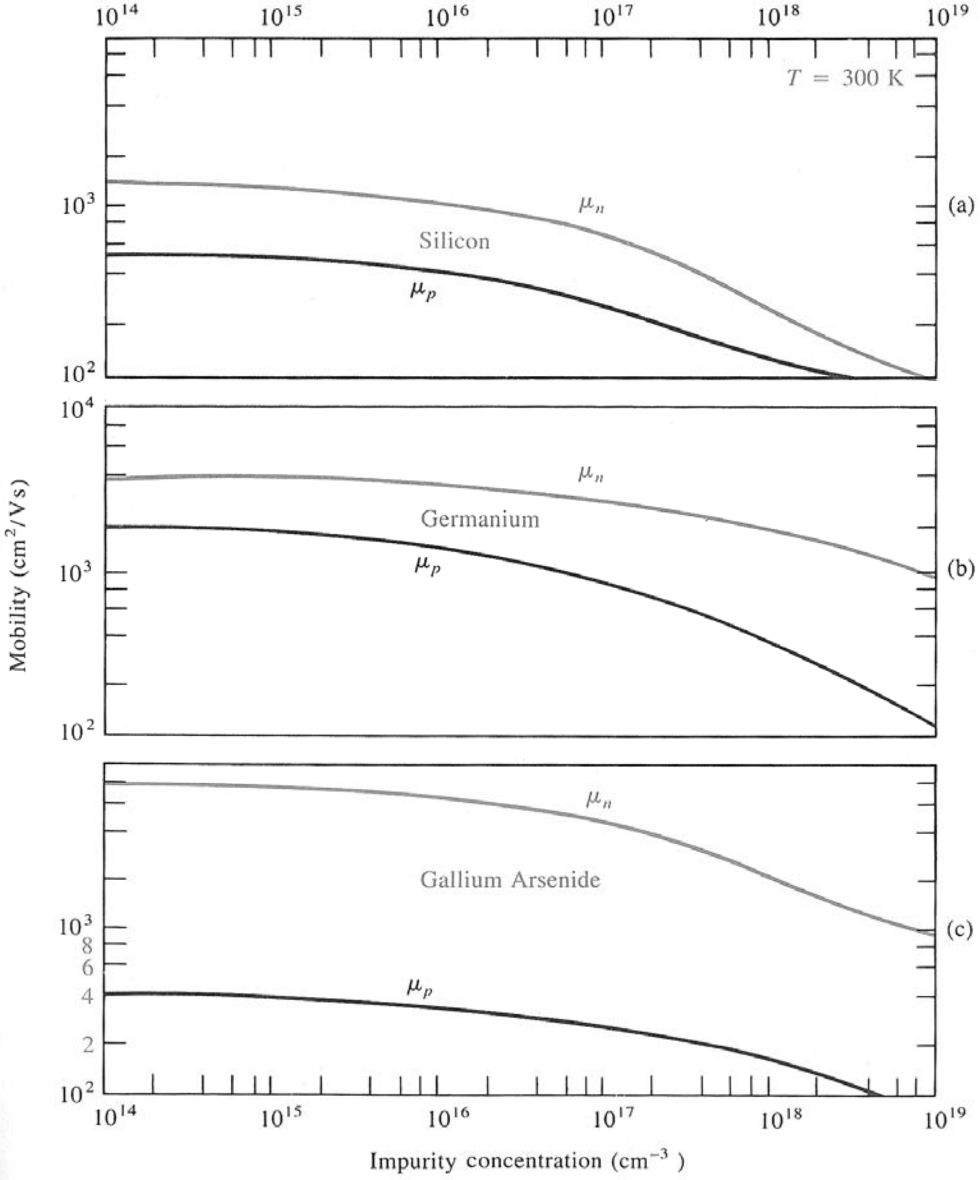


Figure 3-23 Variation of mobility with doping impurity concentration for Ge, Si, and GaAs at 300 K.

Diffusion

- Diffusion arises from a nonuniform density of carriers
- The carriers will diffuse from a region of high density to a region of low density
- The process is identical for neutral and charged particles

Drift + Diffusion

If an electric field is present in addition to a concentration gradient in a semiconductor, the total current density for electrons and holes is given by

$$J_e = qn\mu_e E + qD_e\frac{dn}{dx}$$

$\sigma = nq\mu$

$$J_h = qp\mu_h E - qD_h\frac{dp}{dx} \quad (2.139)$$

in which the first term on the right arises from drift and the second term arises from diffusion. The total current density is the sum of the contributions due to electrons and holes

$$J(x) = J_e(x) + J_h(x) \quad (2.140)$$

Equations 2.139 and 2.140 are called the current density equations. Some important insights regarding the transport processes can be obtained from Eq. 2.139. The drift term is proportional to the carrier density. Since the density of minority carriers in a

Comments

- The density of minority carriers in a semiconductor can be many orders of magnitude smaller than the density of majority carriers, the process of drift is essentially controlled by majority carriers.
- The process of diffusion depends on the concentration gradient. Since the density of minority is small, a concentration gradient of minority carriers is easily produced by current injection in a p-n junction or by intrinsic photoexcitation. Thus, diffusion is essentially controlled by the density of minority carriers.

Velocity

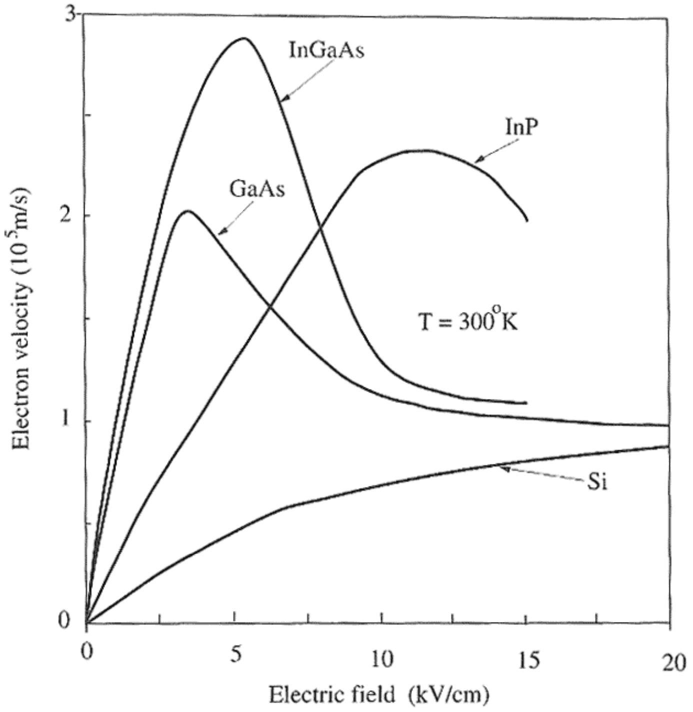
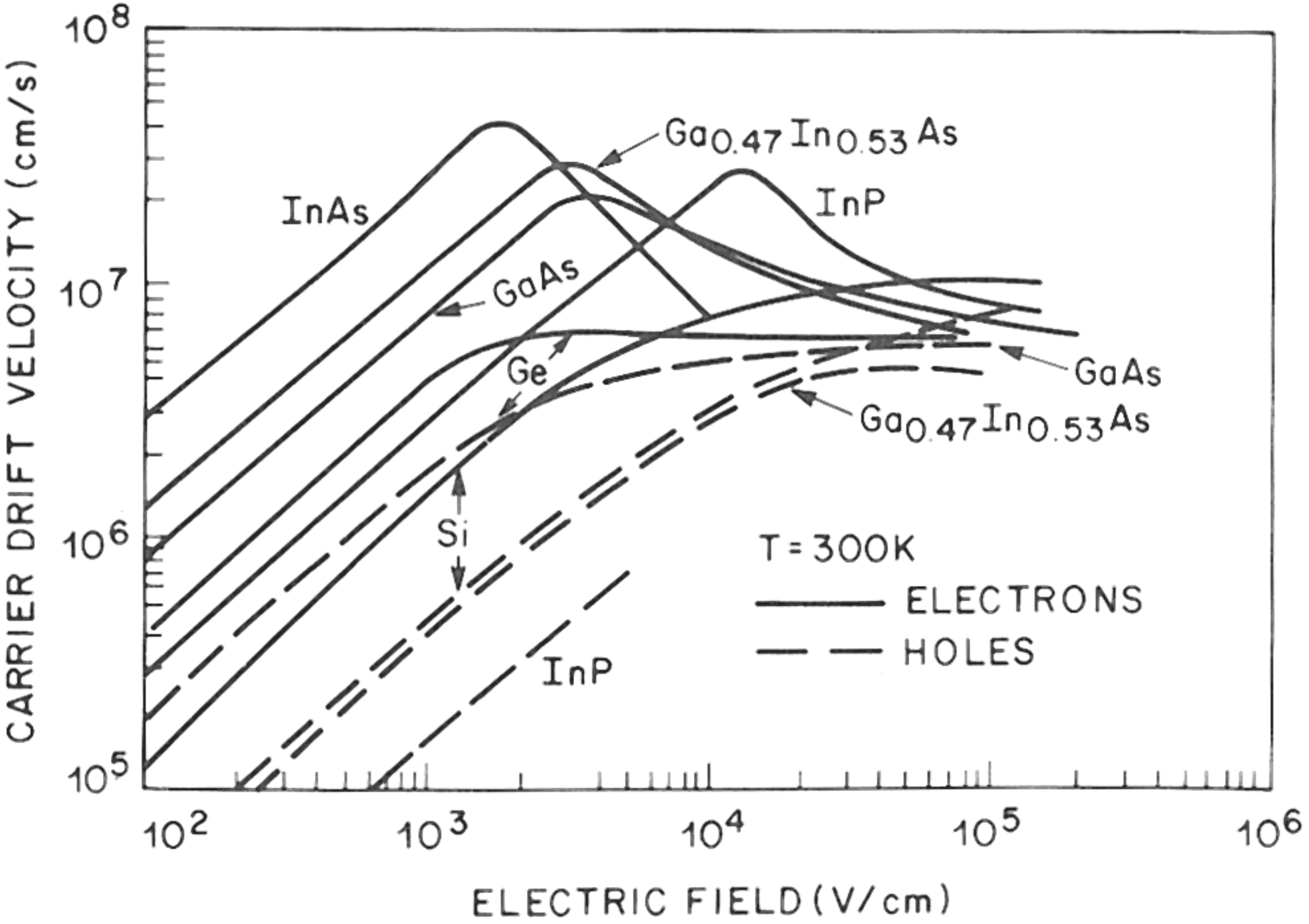


Figure 2.27 Electron drift velocity as a function of electric field at room temperature in elemental and compound semiconductors (from M. Shur, *Physics of Semiconductor Devices*, © 1990. Reprinted by permission of Prentice Hall, Englewood Cliffs, NJ).

field continues to increase, the velocity-field characteristics will now be controlled by the transport parameters of the L minima. Thus, at low fields the velocity is given by $\vartheta = \mu_\Gamma E$ and after carrier transfer $\vartheta = \mu_L E$. In the region in between, there is a *negative differential mobility* given by $\mu = - d\vartheta_D/dE$. In real semiconductors the drift velocity does not continue to increase after carrier transfer, but saturates due to reasons outlined earlier. The phenomenon just described is commonly known as the *Gunn effect*. The important parameters in the velocity-field characteristics are the critical field E_C, which marks the onset of the carrier transfer process and the peak and saturation velocities.

Electron Transferred Effect

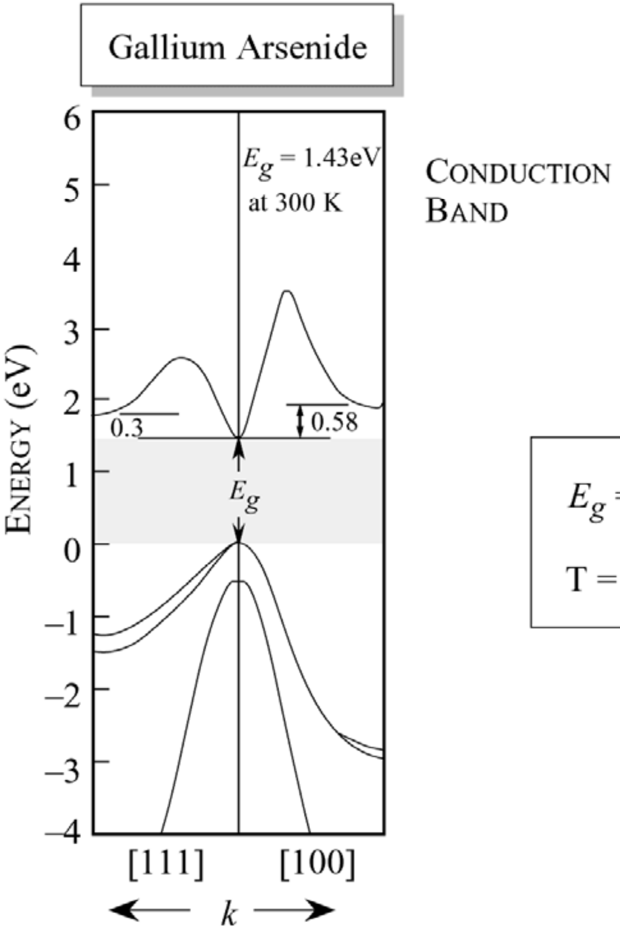


$v = \mu E$

$\mu = dv/dE$

GaAs Band Structure

The bandgap at 0 K is 1.51 eV and at 300 K it is 1.43 eV. The bottom of the conductionband is at $k = (0,0,0)$, i.e., the G-point. The upper conduction band valleys are at the L-point.

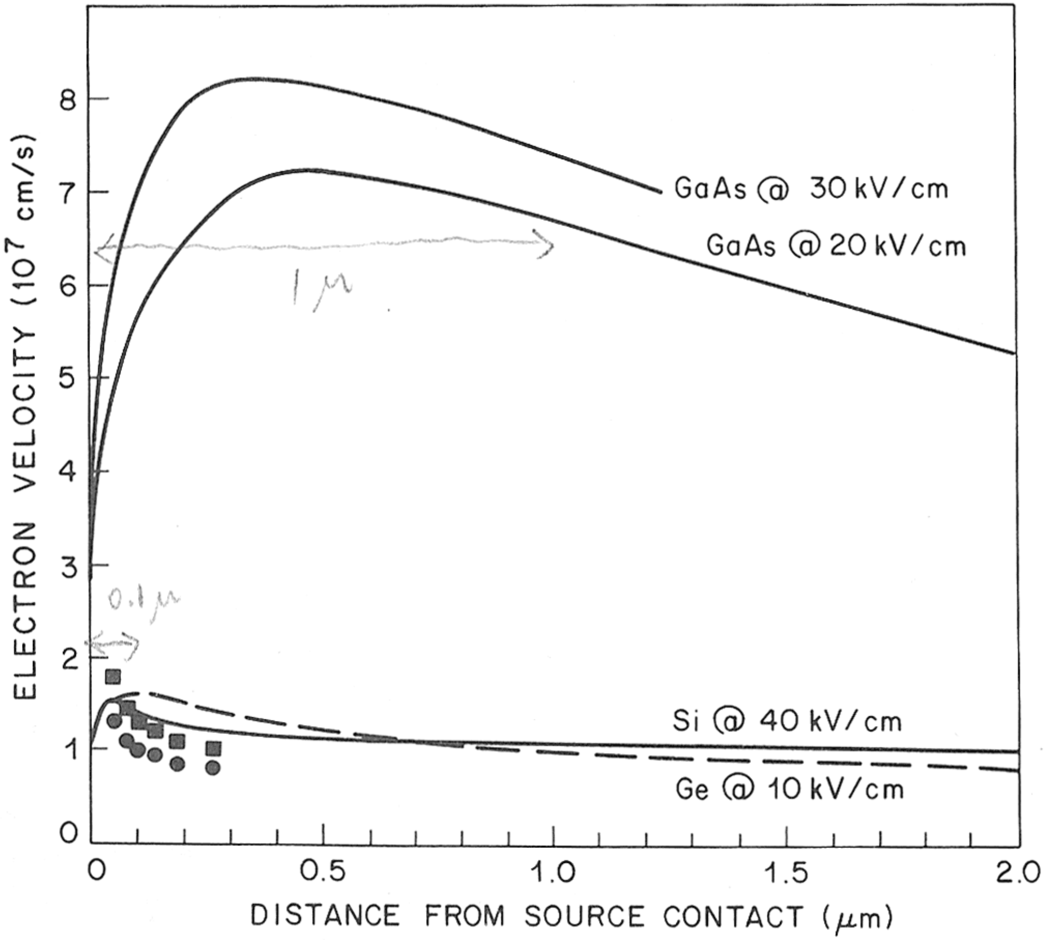


$$E_g = 1.519 - \frac{5.4 \times 10^{-4}\, T^2}{T + 204} \text{ (eV)}$$

T = Temperature in K

Velocity Overshooting

Non-equlibrium

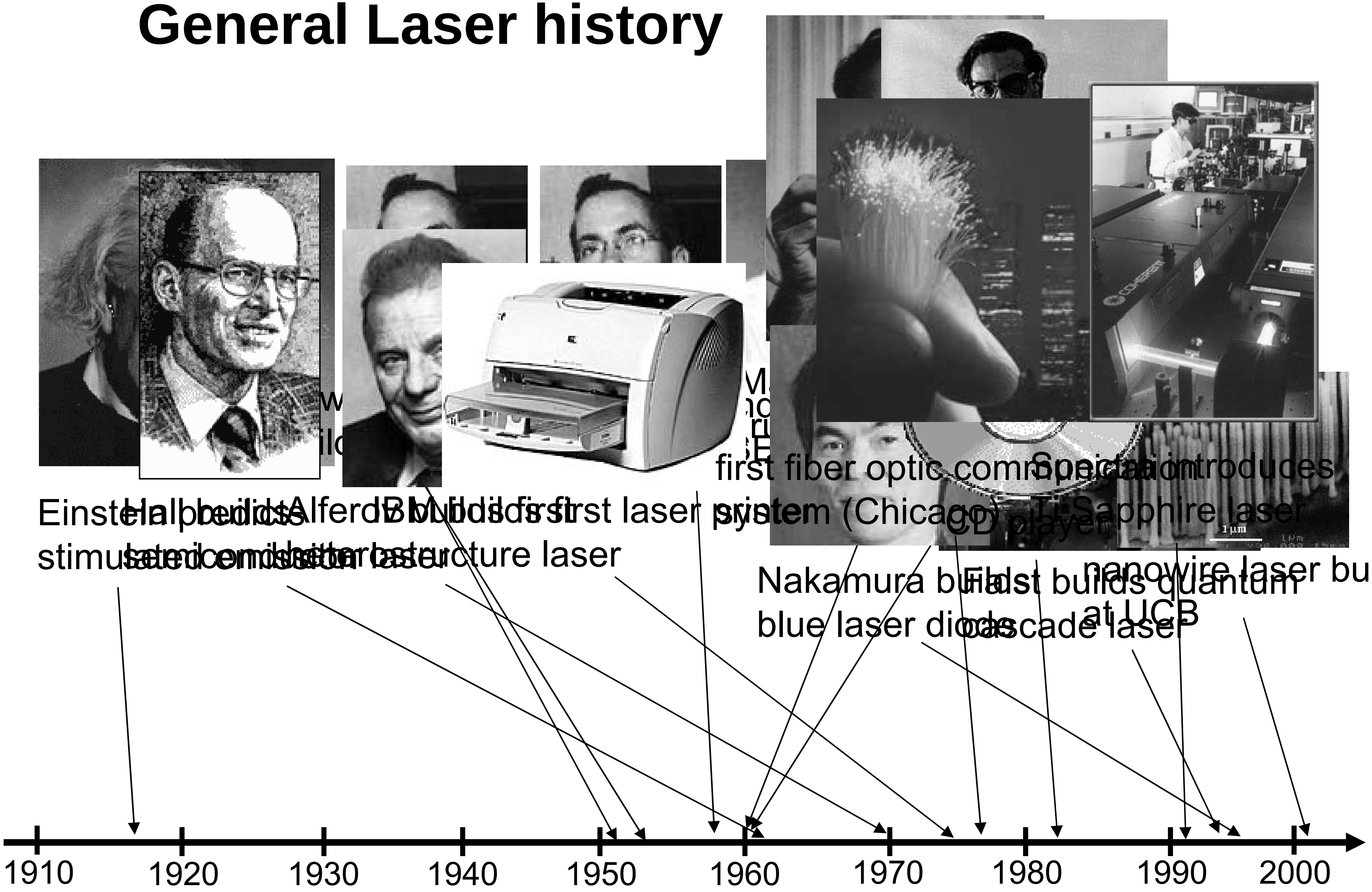


Introduction of Devices

Semiconductor Laser Diode

- Introduction
- Confinement structure
- Material
- LD varieties

General Laser history



Einstein predicts stimulated emission

Hall builds semiconductor laser

Alferov builds first heterostructure laser

IBM builds first laser printer

first fiber optic communication system (Chicago)

CD player

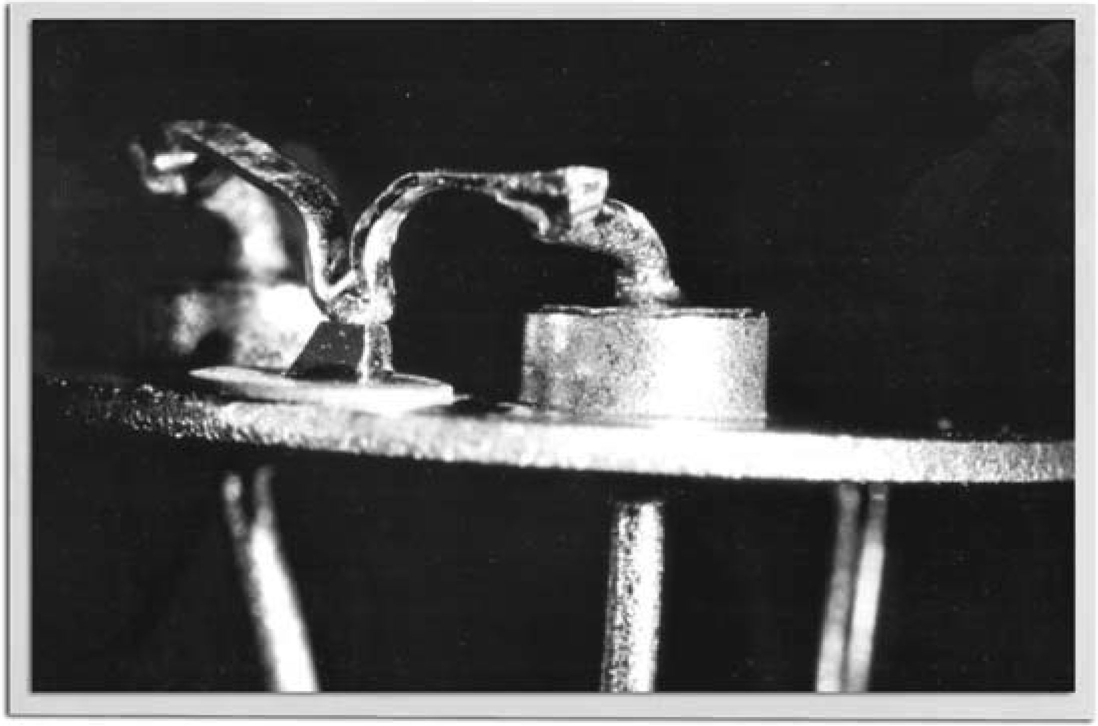
Spectra introduces Ti-Sapphire laser

Nakamura builds blue laser diodes

Faist builds quantum cascade laser

nanowire laser built at UCB

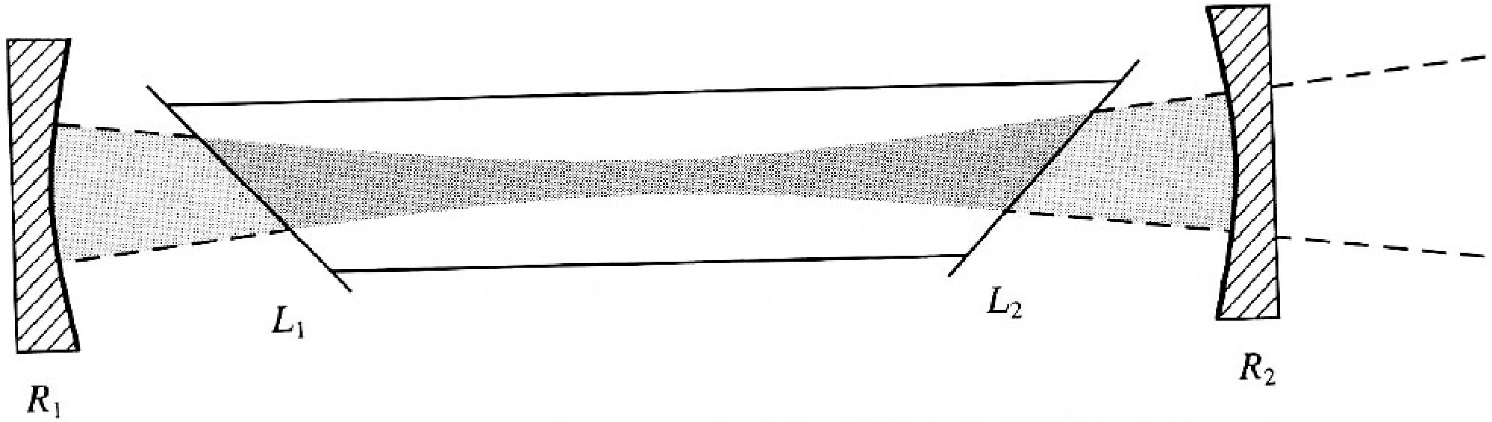
First Semiconductor Laser



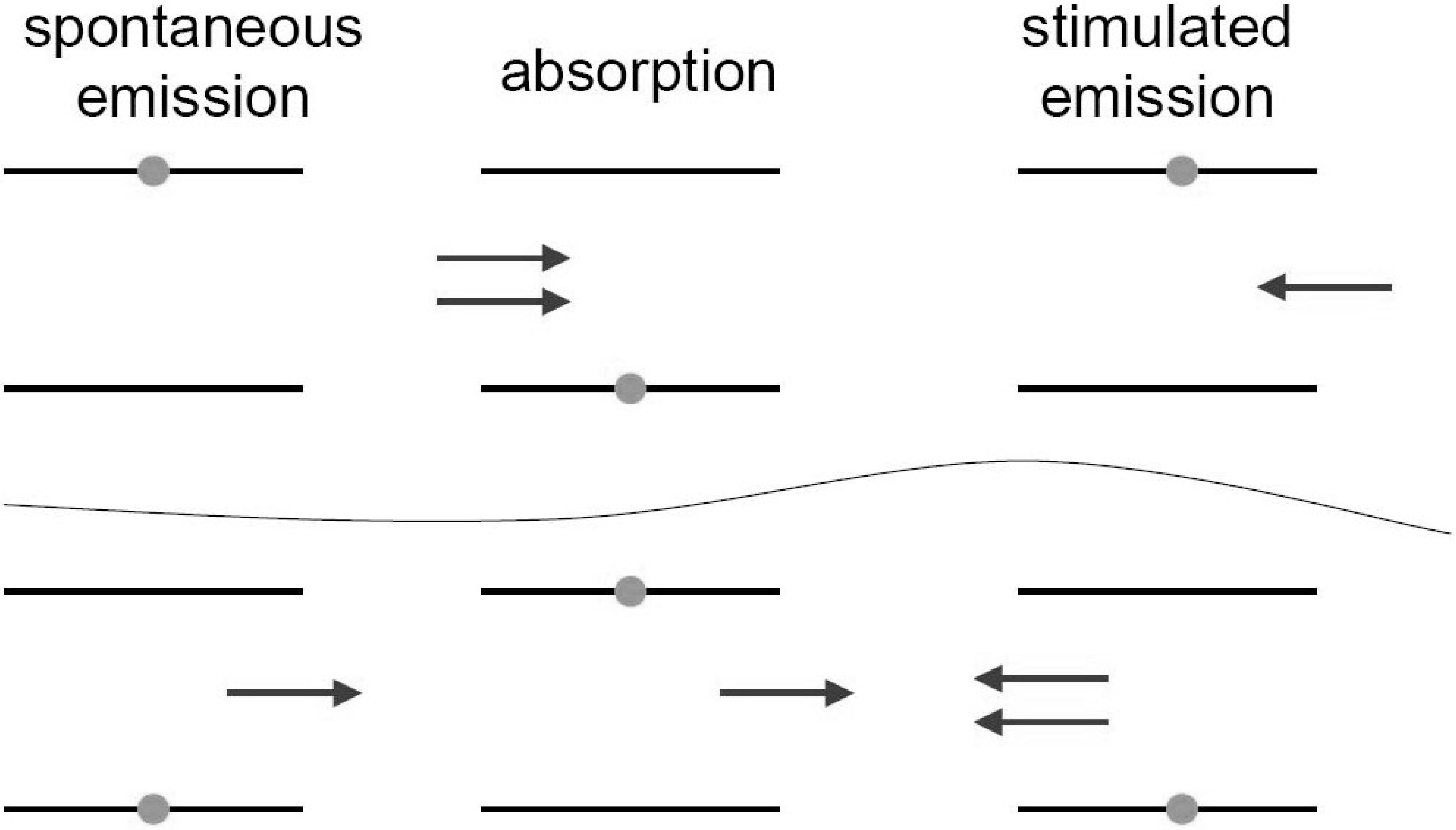
GaAs with a diffused p-n junction, it had polished facets and operated under pulsed conditions at cryogenic temperatures. (GE corporate research lab)

Oscillator

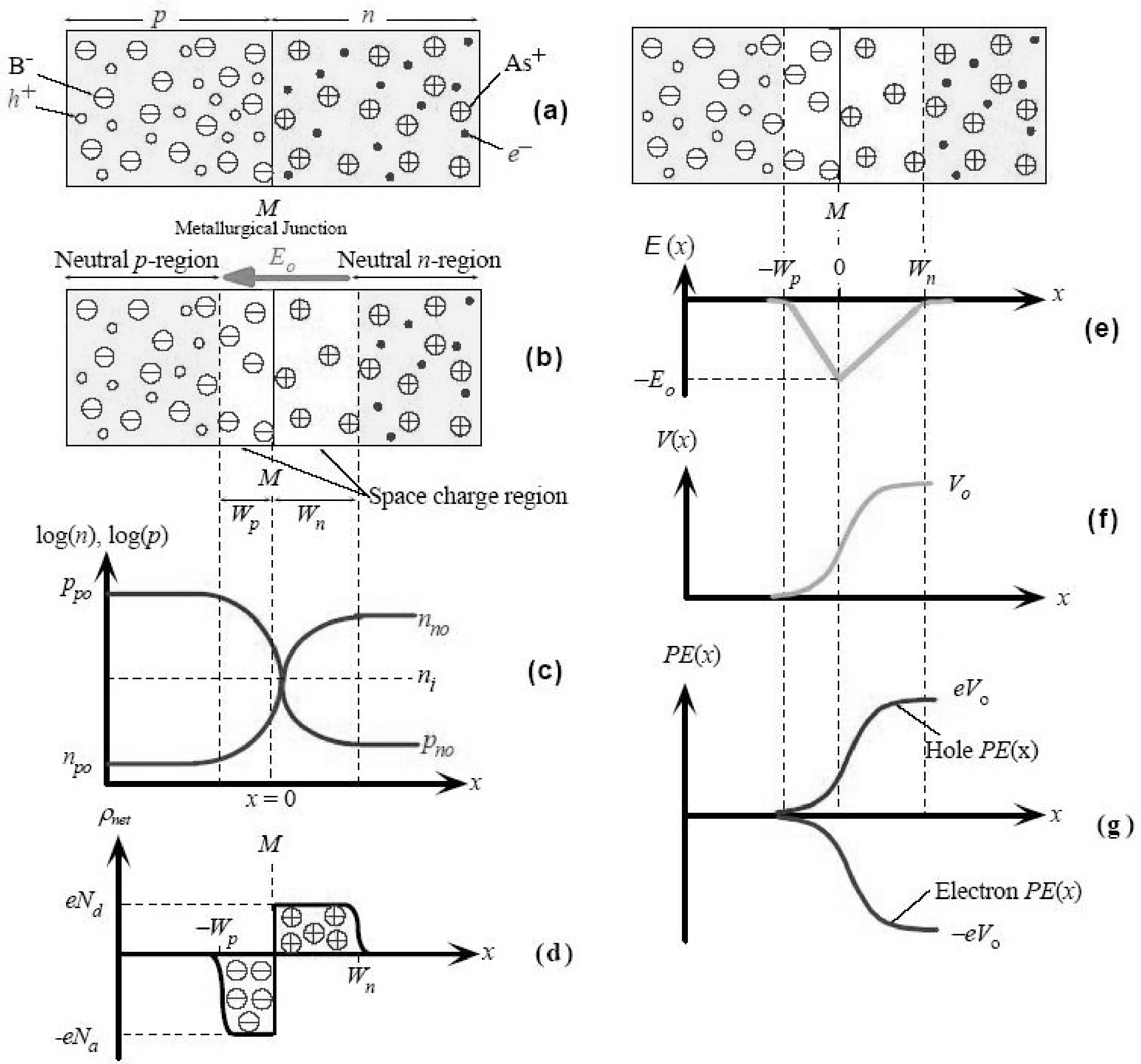
- **An oscillator is just an amplifier (gain medium) with feedback.**



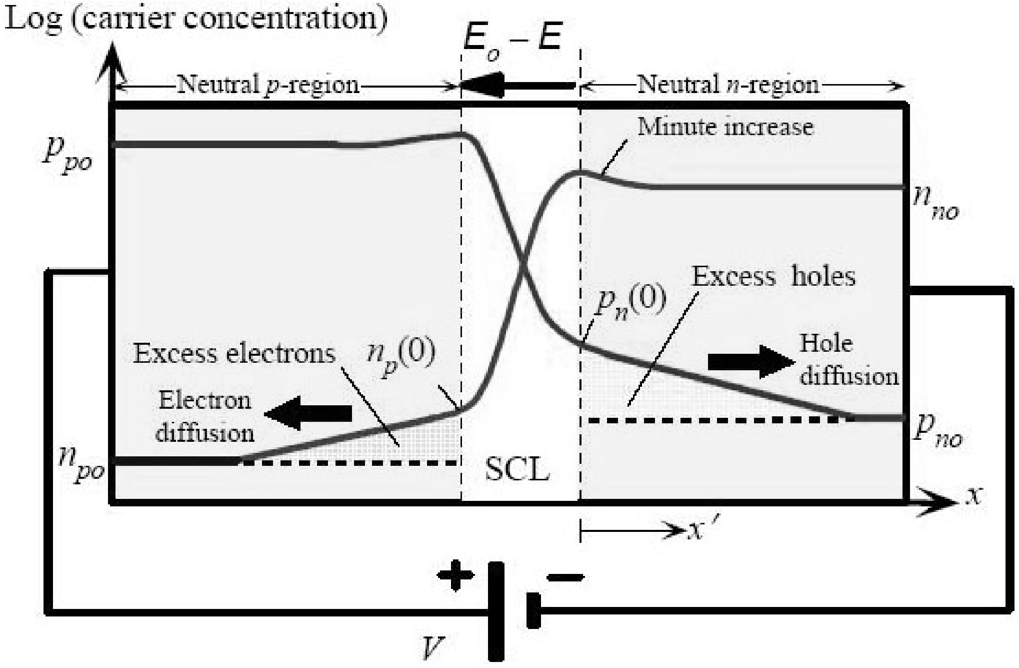
Optical Processes



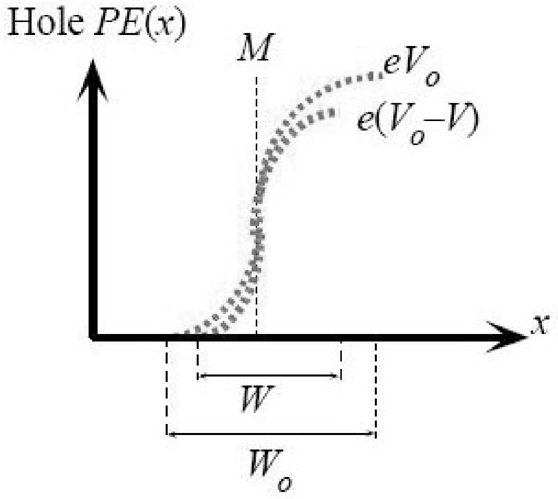
Semiconductor p-n Junction



Forward Bias

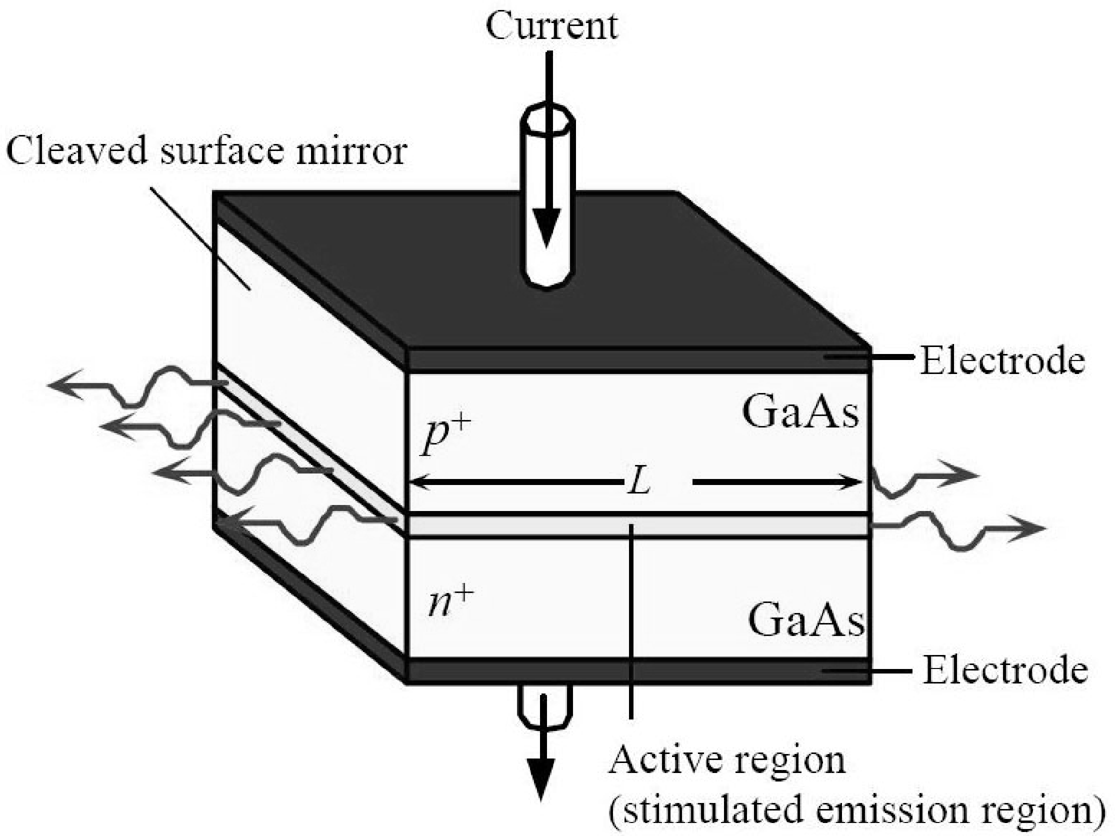


(a)



(b)

LD Schemetic



Semiconductor Laser Diode

- Introduction
- Confinement structure
- Material
- LD varieties

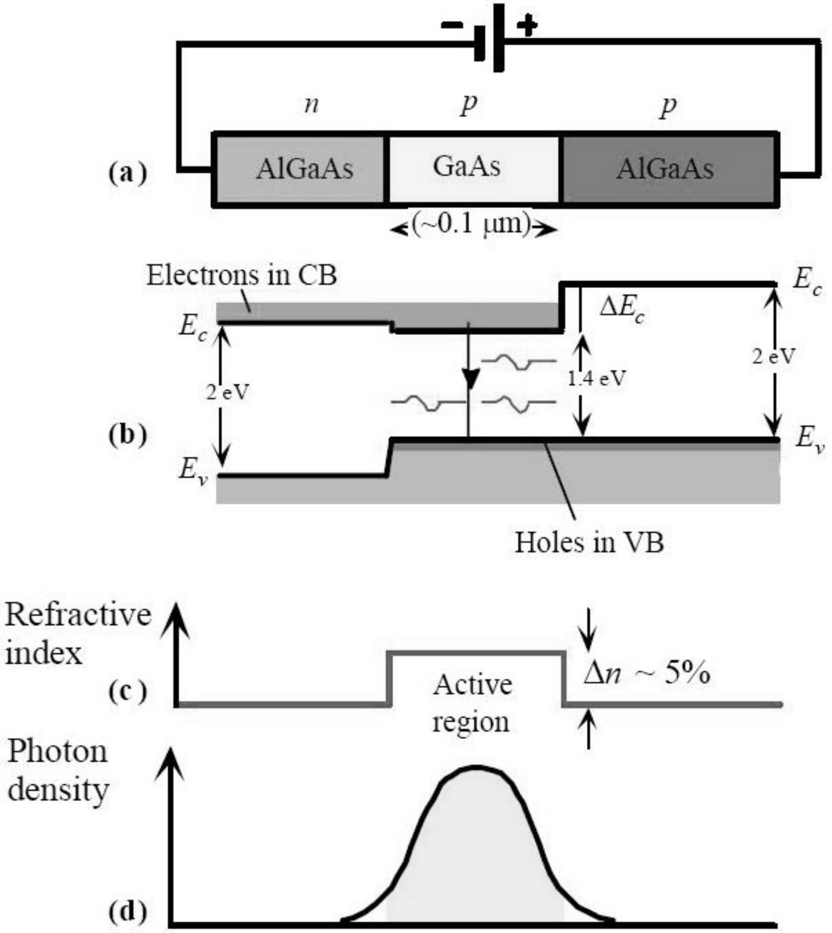
Geometric Design Considerations

- Electrical carriers confinement
  - Radiative recombination dominates
  - Minimize the drift and diffusion current
- Optical transverse confinement
  - Waveguide
  - Mode profile engineering
  - Enhance the overlapping between the optical mode and the carrier confinement region (improved stimulated emission)

Vertical Structure Evolution

- Homojunction
- Single heterostructure (nobel prize)
- Double heterostructure
- Separate confinement heterostructure (SCH)
- Multiquantum well active
- Graded index-SCH

Double Heterostructure LD



(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*

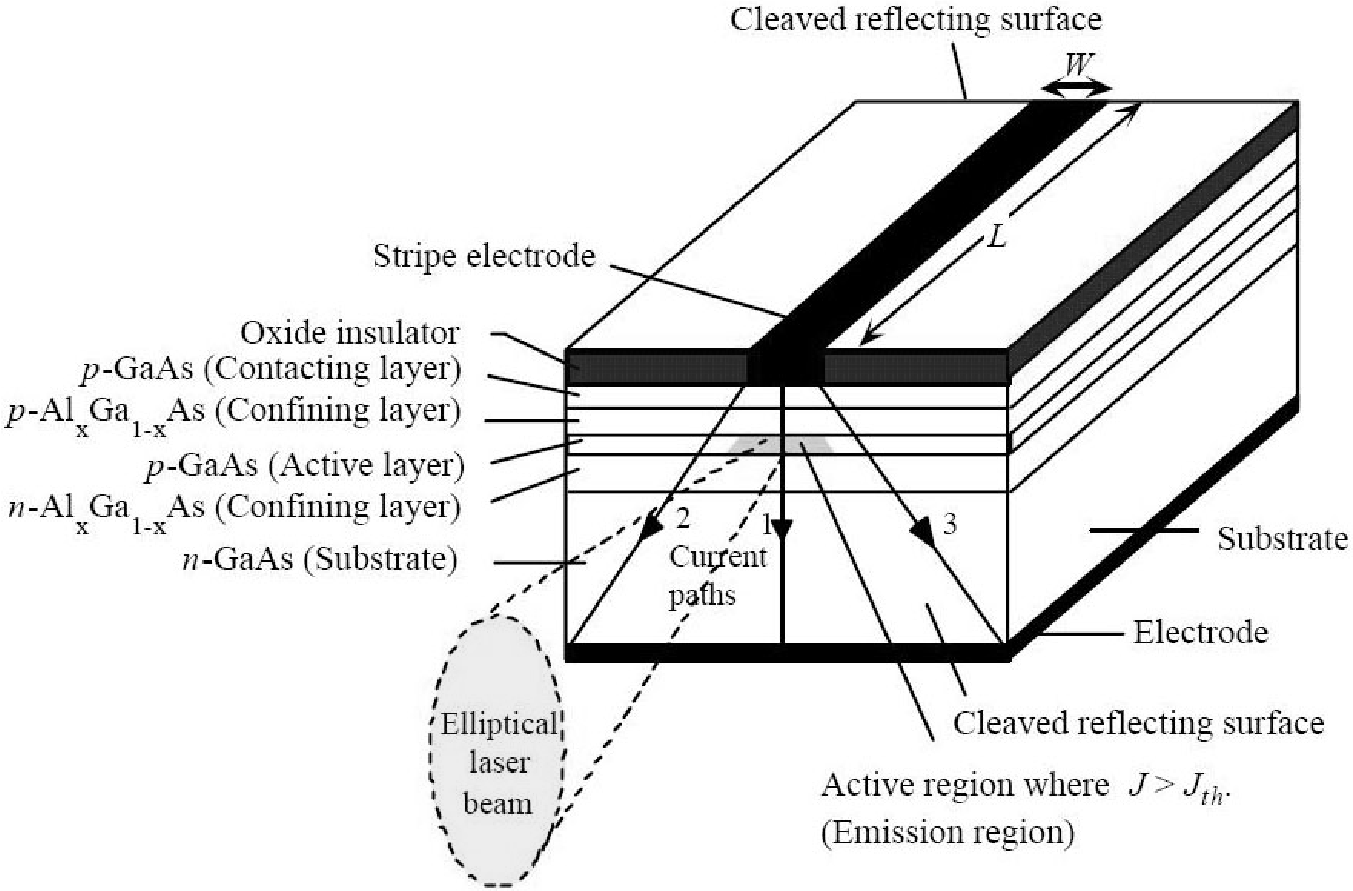
(c) Higher bandgap materials have a lower refractive index

(d) AlGaAs layers provide lateral optical confinement.

Lateral Structure Evolution

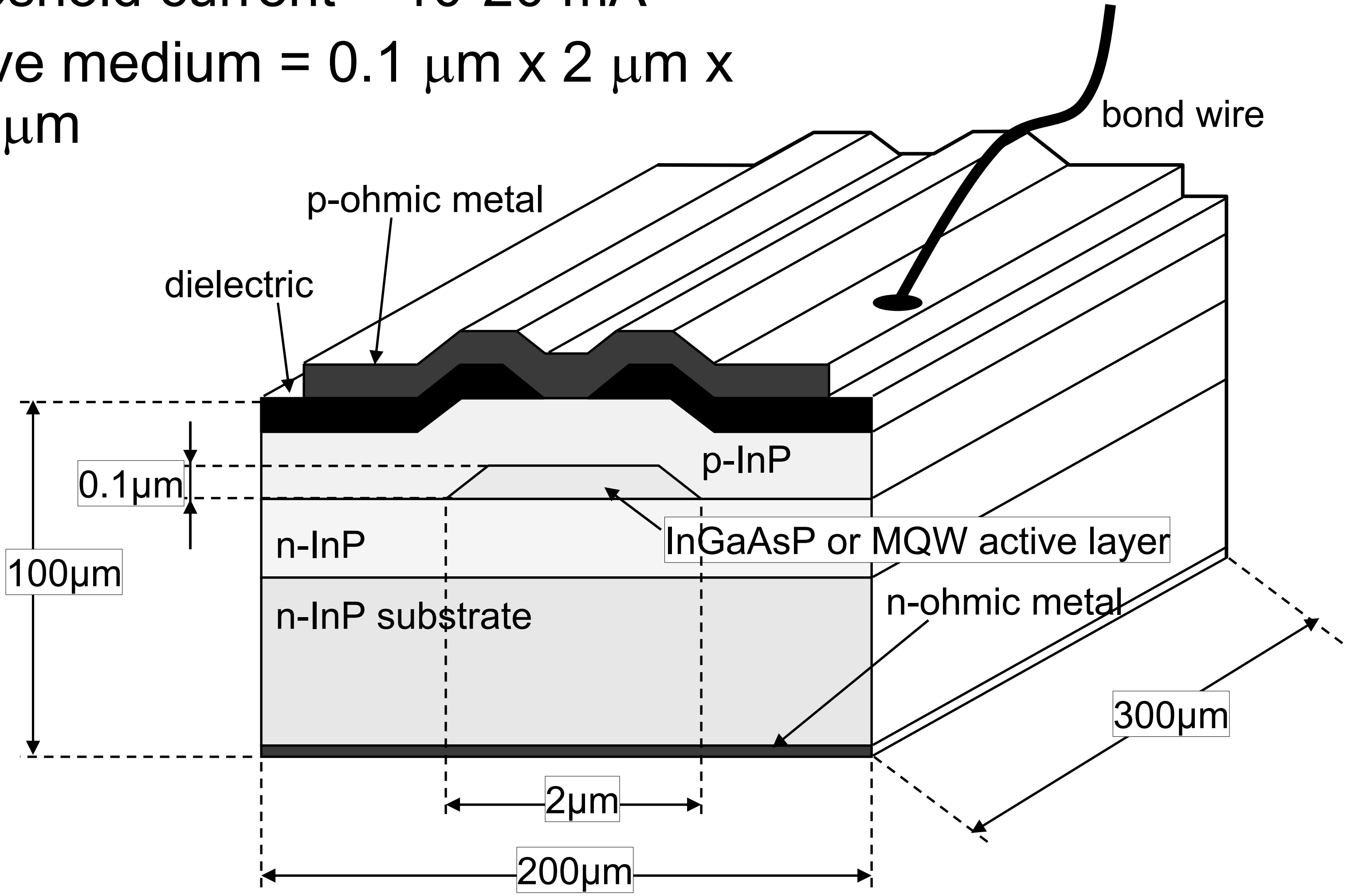
- Broad area - no lateral guiding
- Strip geometry
  - Gain guiding
    - Metal contact stripe
    - Proton-bombarded
    - Zn diffused
    - Ridge waveguide
    - Channel substrate
  - Index guiding
    - Buried heterosturcture (BH)
    - V-grooved substrate BH
    - Double channel planar BH

Gain Guiding



Index Guiding

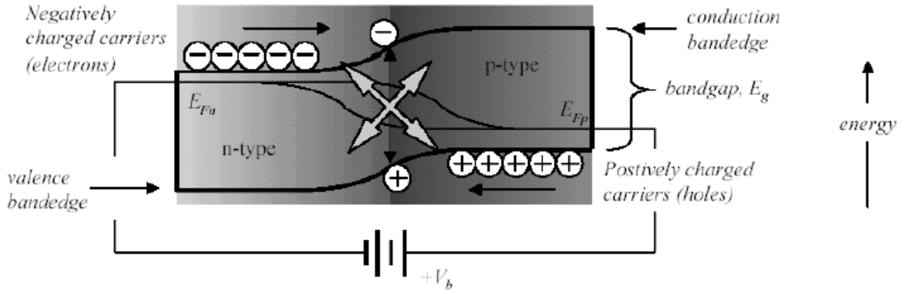
- Threshold current = 10-20 mA
- Active medium = 0.1 μm x 2 μm x 300 μm

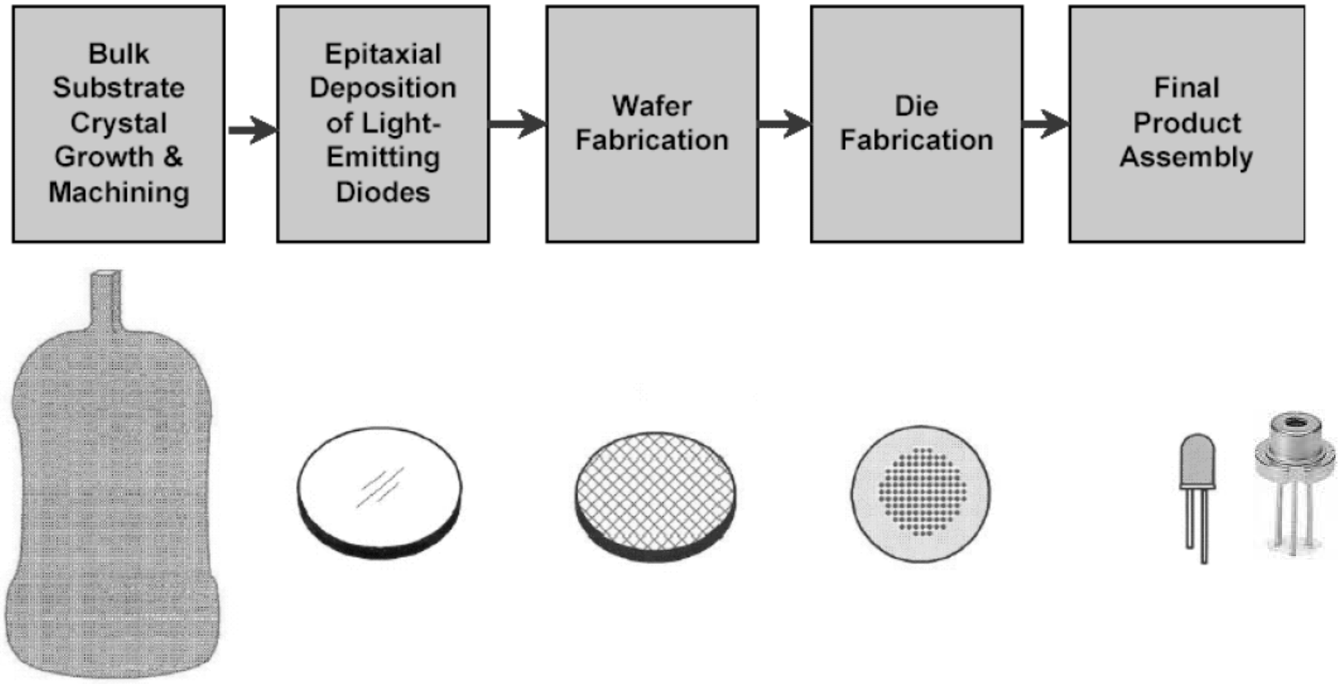


Semiconductor Laser Diode

- Introduction
- Confinement structure
- Material
- LD varieties

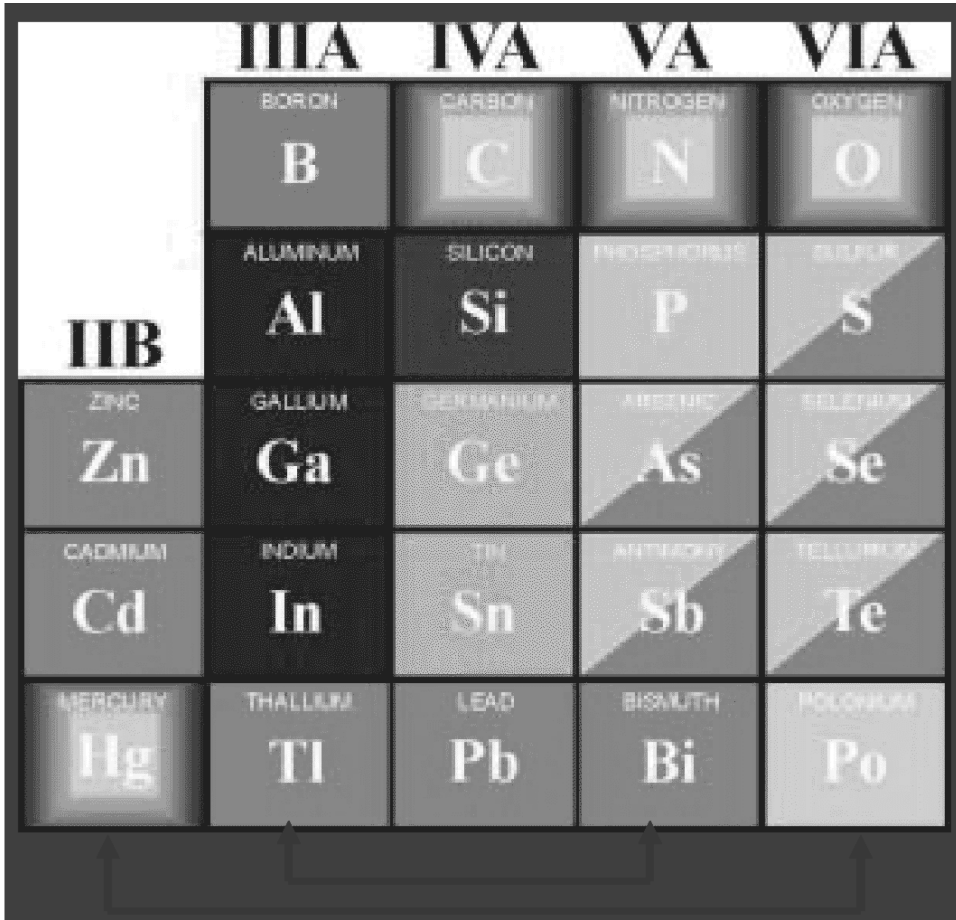
無機半導體發光元件基礎





Bulk Substrate Crystal Growth & Machining → Epitaxial Deposition of Light-Emitting Diodes → Wafer Fabrication → Die Fabrication → Final Product Assembly

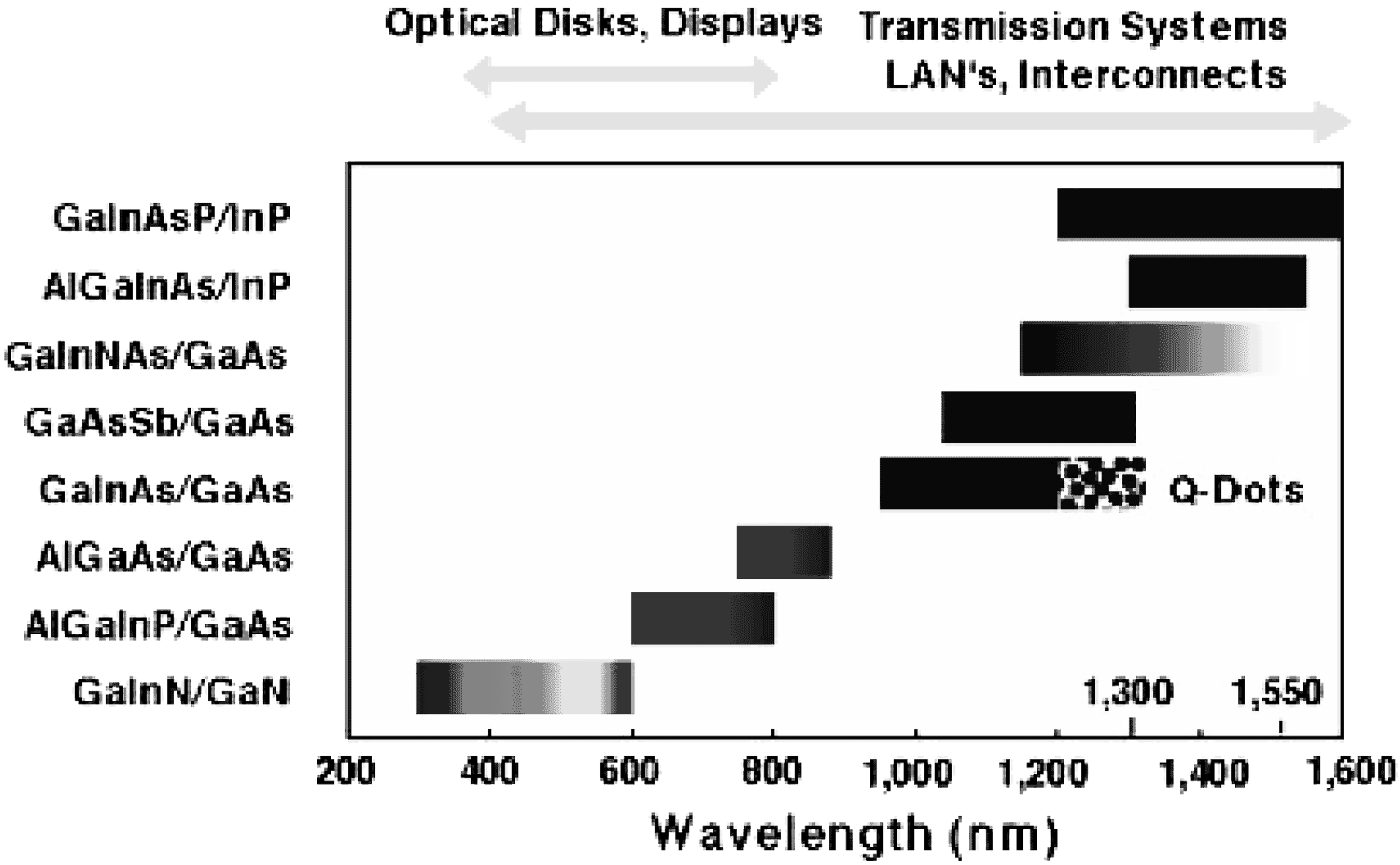
Compound Semiconductor



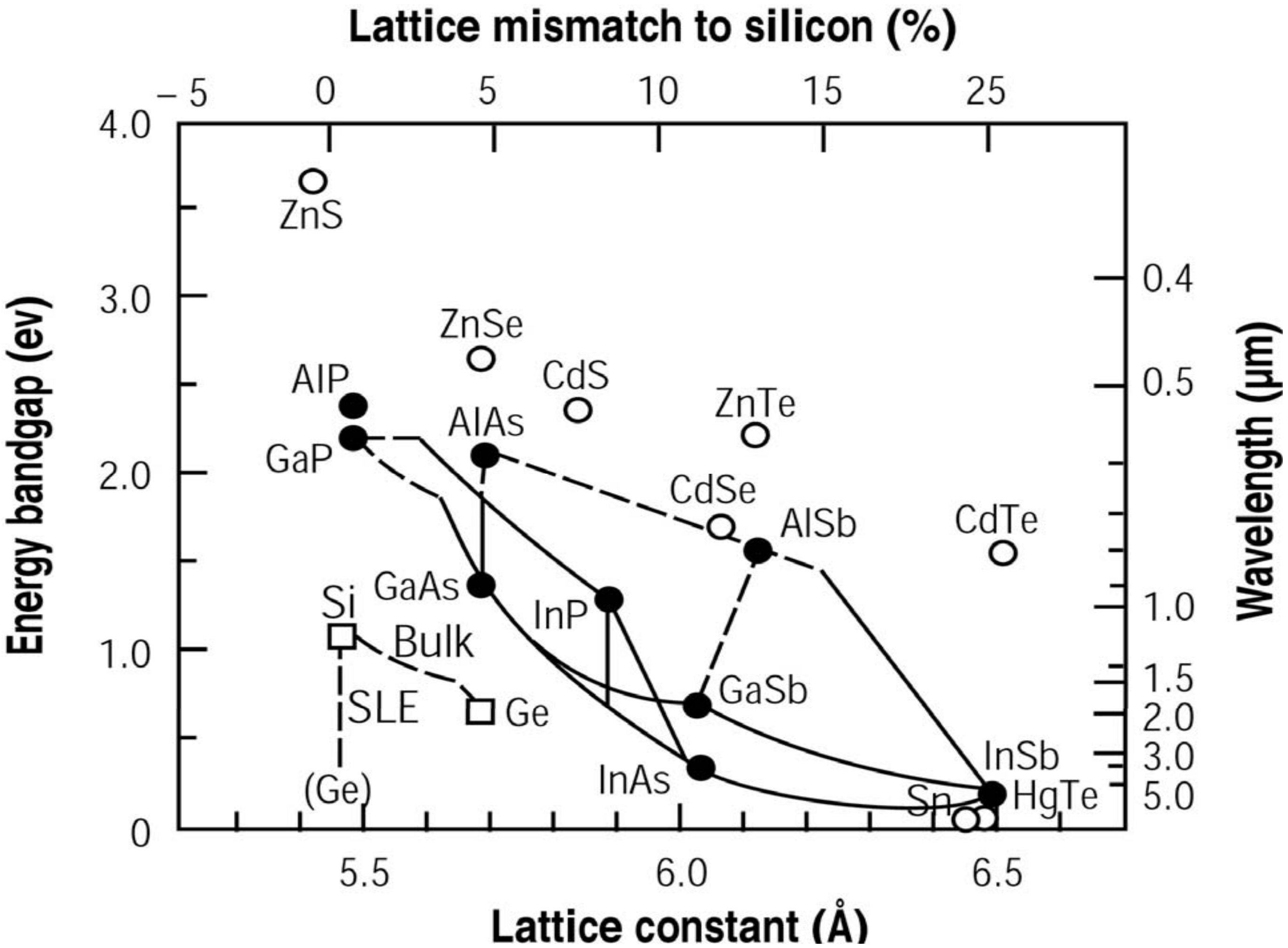
MOCVD

- most MBE work has focused on "III-V" (three-five) materials. The III-V materials are combinations of elements from Group III of the periodic table, gallium (Ga), indium (In), and aluminum (Al), and the Group V elements arsenic (As), phosphorus (P), antimony (Sb), and nitrogen (N).
- "II-VI" materials using the Group II elements zinc (Zn), cadmium (Cd), and mercury (Hg), and the Group VI elements sulfur (S), selenium (Se), and tellurium (Te).

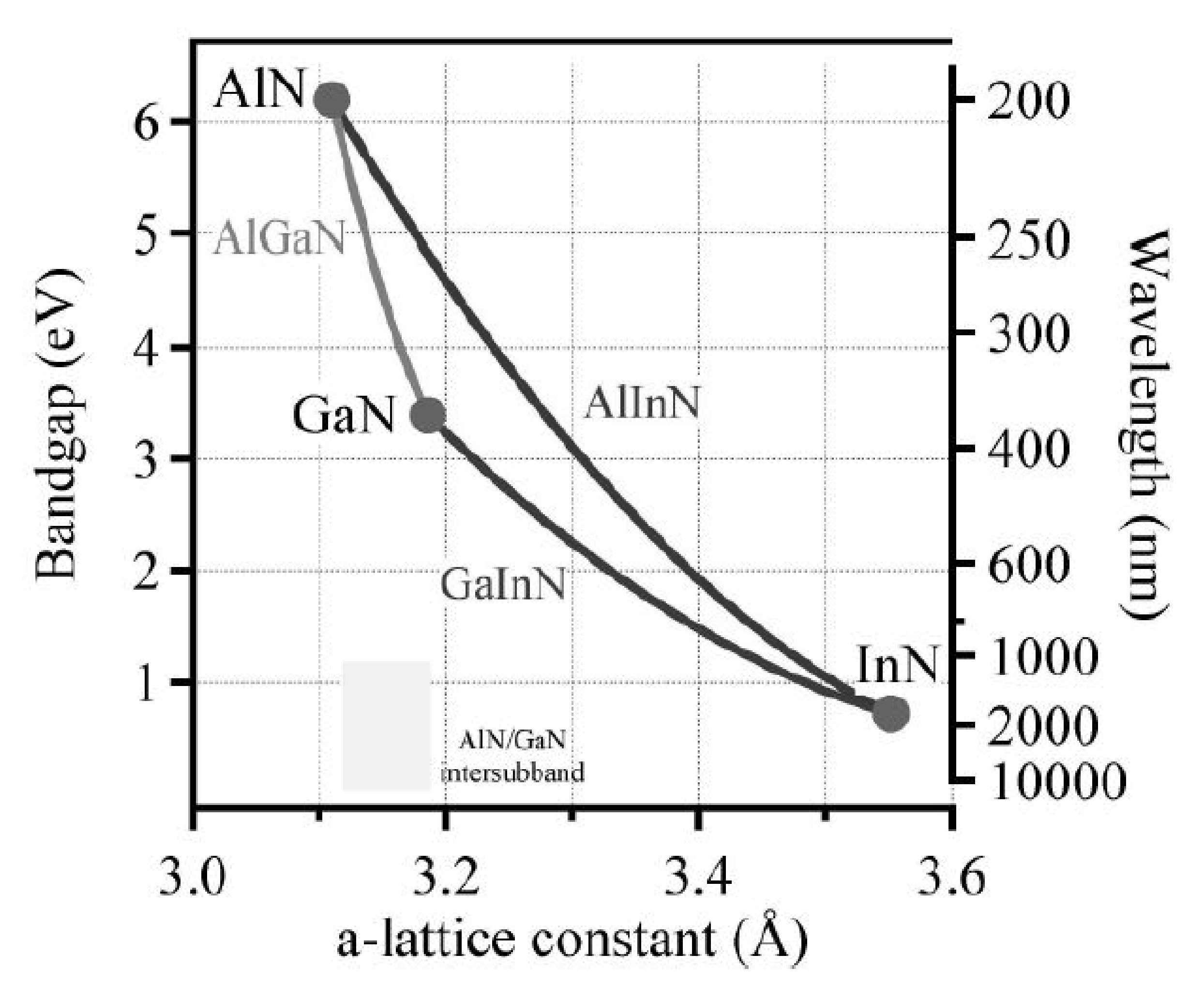
LD 材料選擇


Optical Disks, Displays
Transmission Systems
LAN's, Interconnects
GaInAsP/InP
AlGaInAs/InP
GaInNAs/GaAs
GaAsSb/GaAs
GaInAs/GaAs
Q-Dots
AlGaAs/GaAs
AlGaInP/GaAs
GaInN/GaN
1,300
1,550
200
400
600
800
1,000
1,200
1,400
1,600
Wavelength (nm)

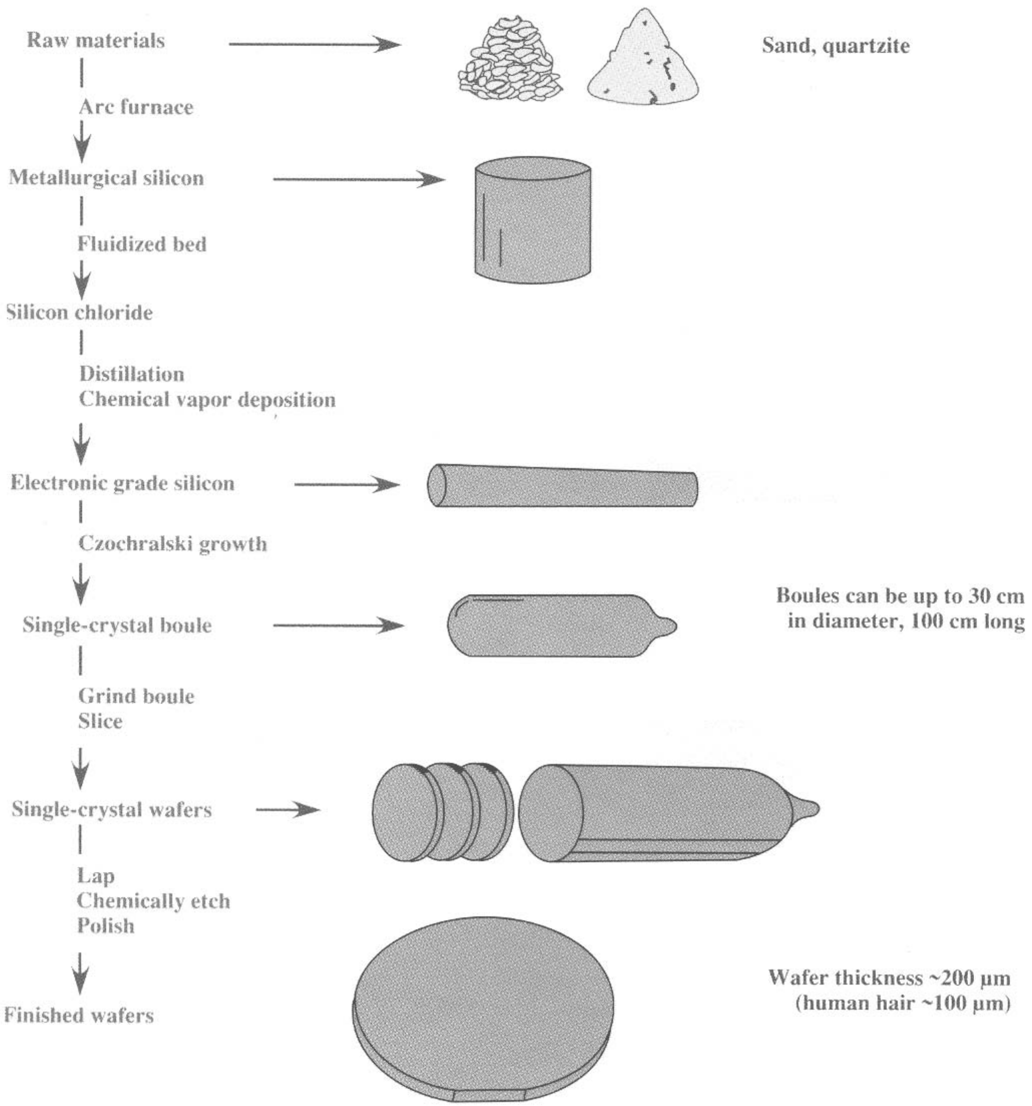
Material Selection



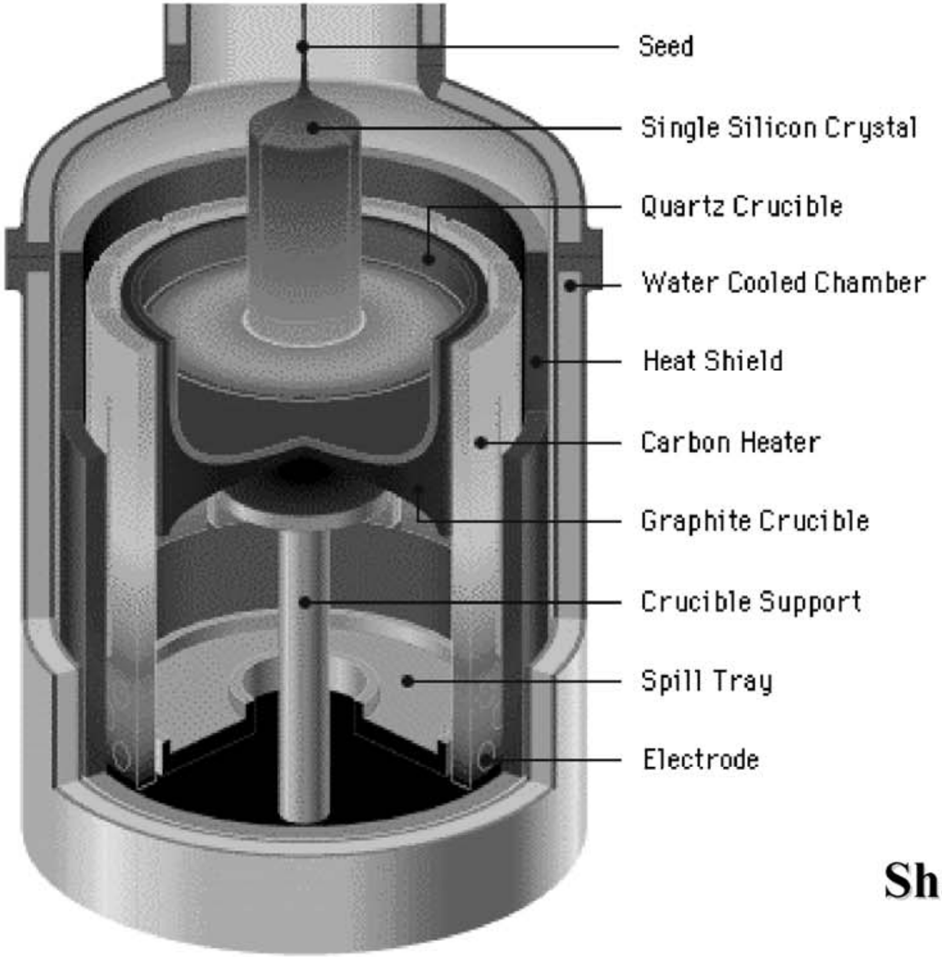
Nitride Based Material



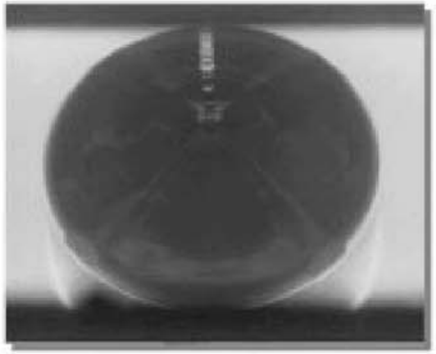
Inorganic Wafer Production



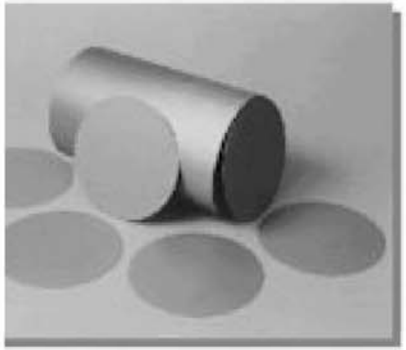
CZ Crystal Growth



Crystal Pulling



Crystal Ingots

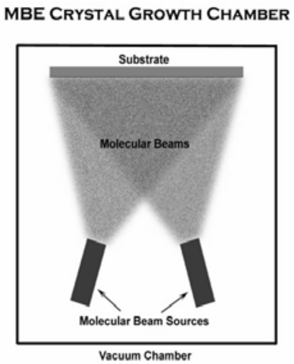


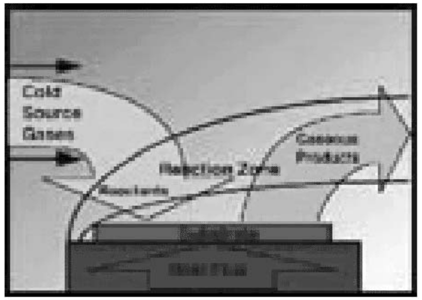
Shaping and Polishing

300 mm wafer

Epitaxy Comparison

- MBE
  - Ultra high vacuum (10^{-10} torr)
  - Long downtime
  - High maintenance cost
  - Slow growth rate (1 atomic layer /sec)
  - Better thickness and interface control
- MOCVD
  - Can grow under atmospheric pressure
  - Dangerous toxic gases
  - High growth rate
  - Low cost
- LPE
  - Low defect material
  - Poor surface morphology
  - Inability to grow extremely thin layers with abrupt interfaces
  - cheap equipment

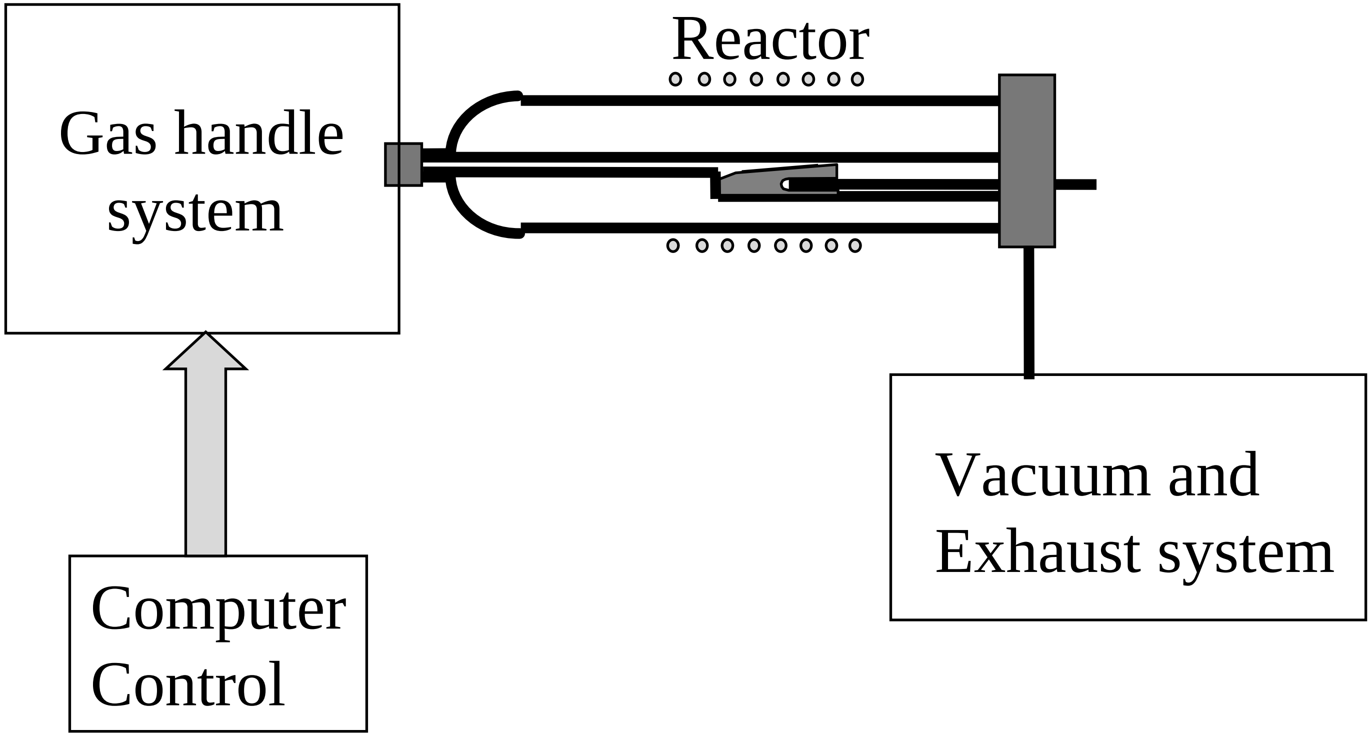




Chemical Vapor deposition (CVD)

Liquid-phase epitaxy LPE)

MOCVD System



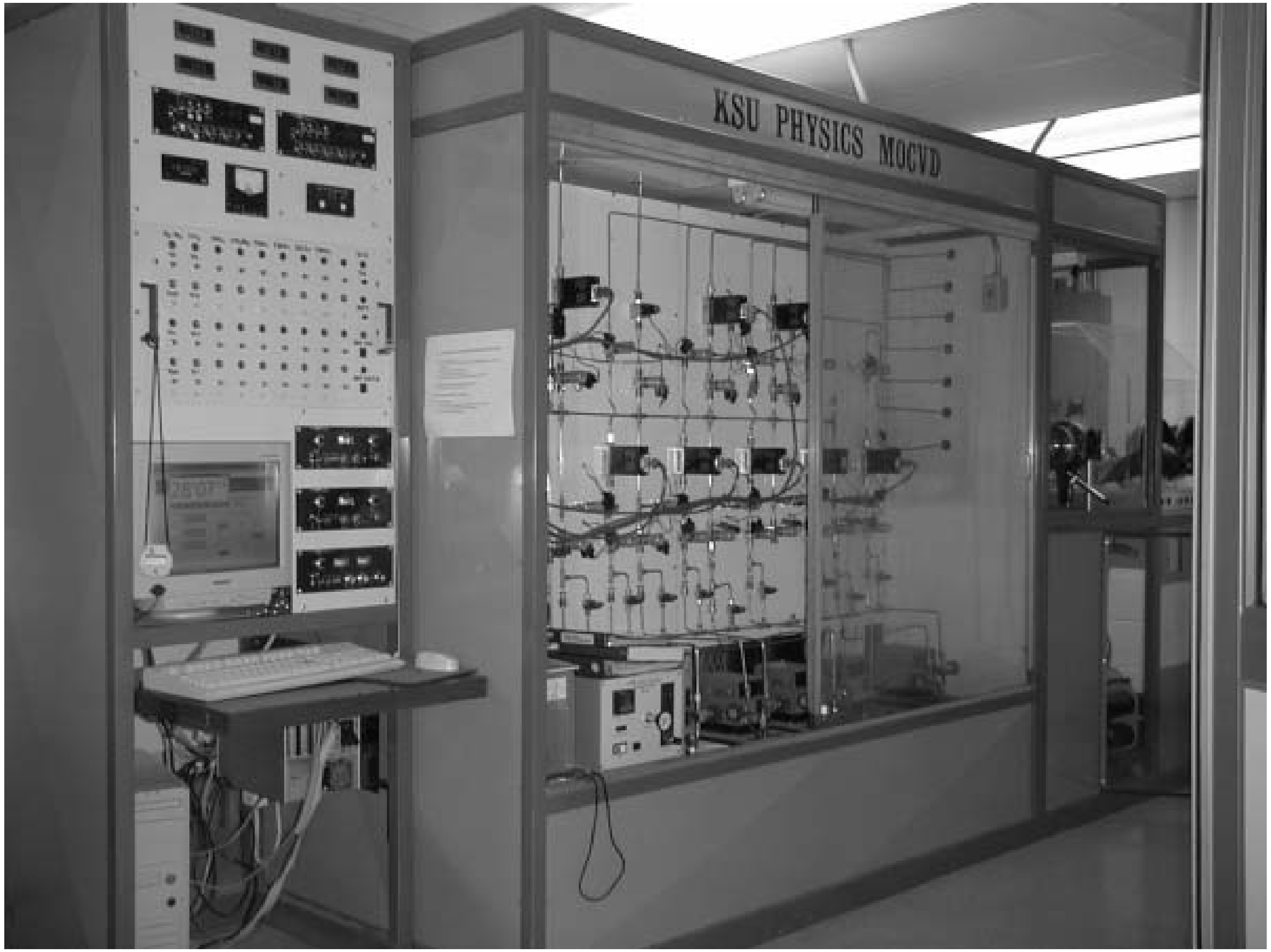
Reactor

Gas handle system

Computer Control

Vacuum and Exhaust system

Control and Gas Handling



AIXTRON 2000

Material Considerations

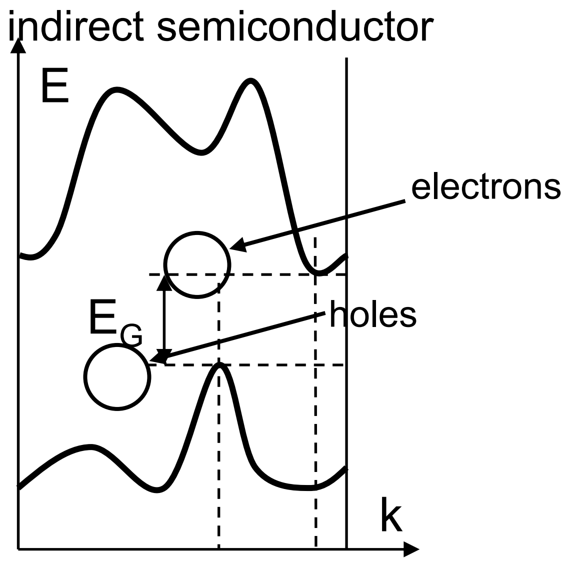
- Direct bandgap material
- Substrate lattice has to match the intended active material
- Ternary or quaternary materials
- Strained quantum wells
- Regrowth

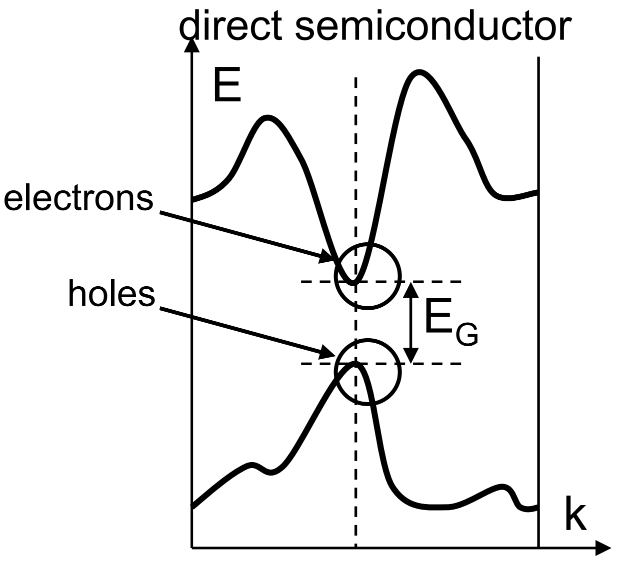
Direct and Indirect Bandgap

Energy bands depend on *k* (momentum)

Indirect semiconductor:
recombination must involve a change in momentum (Si, Ge)

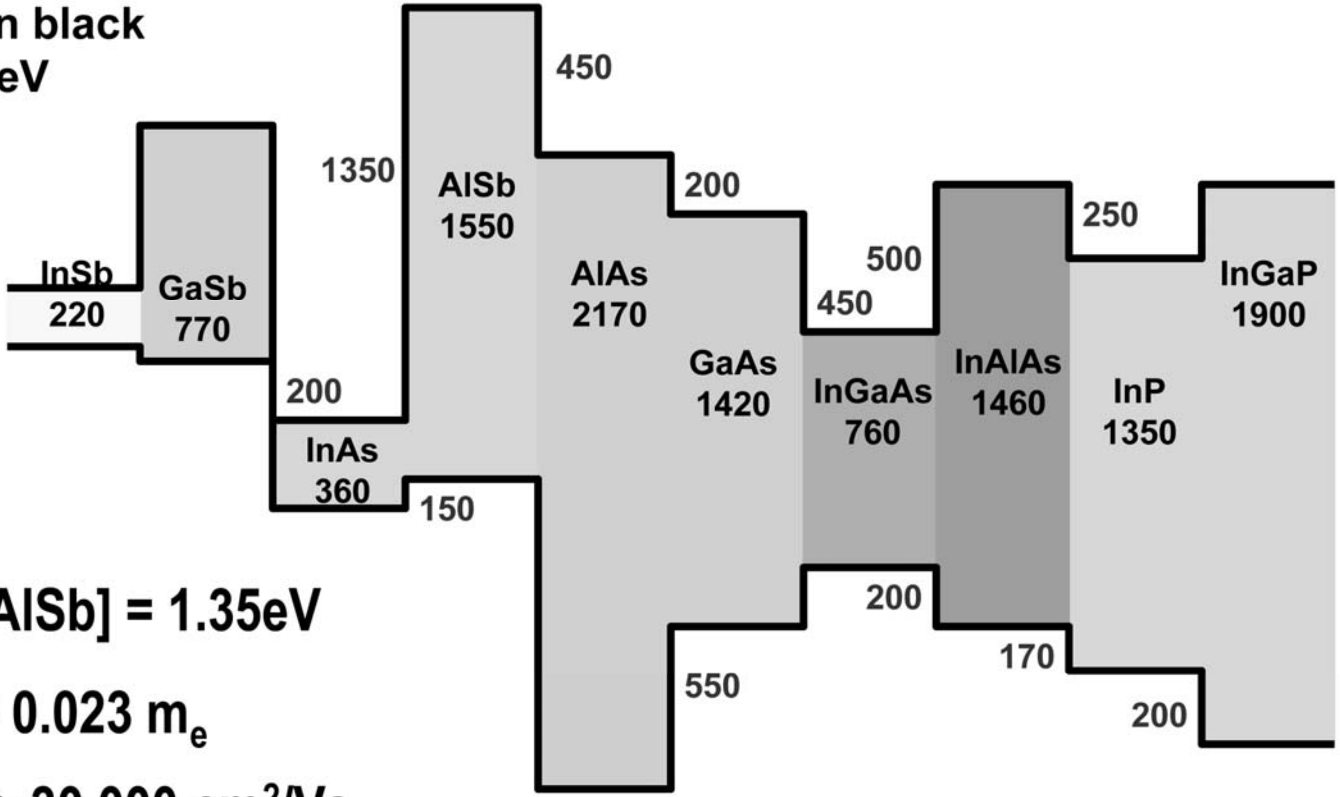
Direct semiconductor:
electron and hole can easily recombine (GaAs, InP)





Band offset

- Offsets in blue #s
- Bandgaps in black
- Units are meV

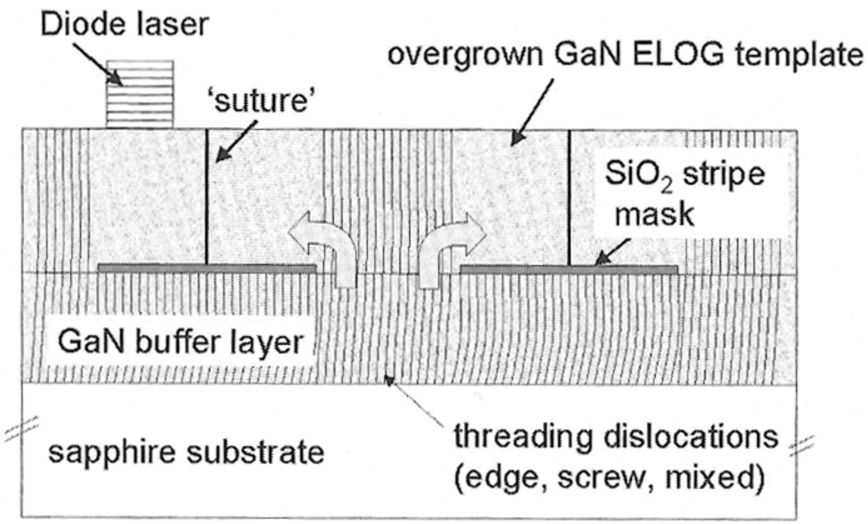


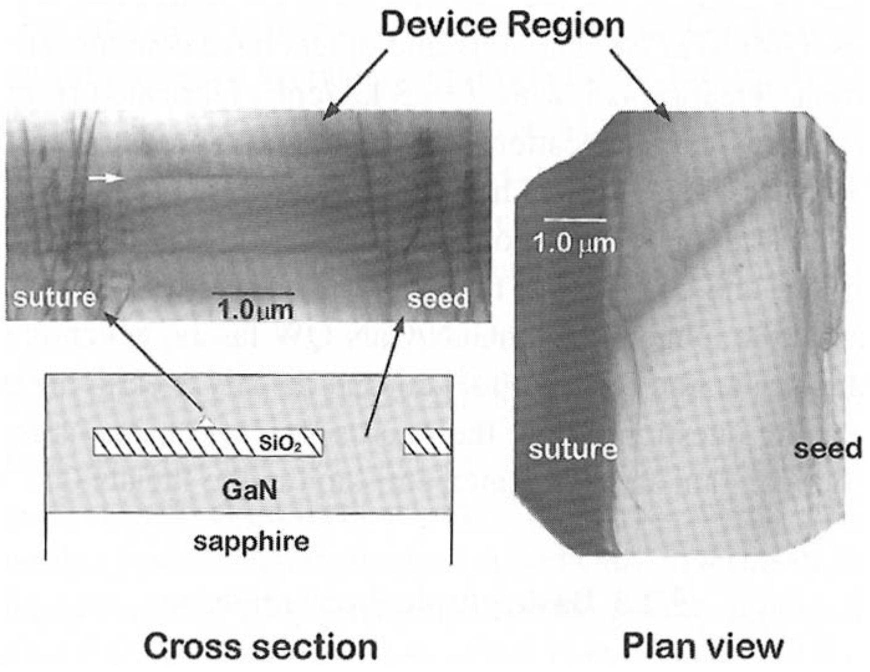
ΔE_C [InAs-AlSb] = 1.35eV

m* [InAs] = 0.023 m_e

InAs RT μ > 30,000 cm^2/Vs

ELOG

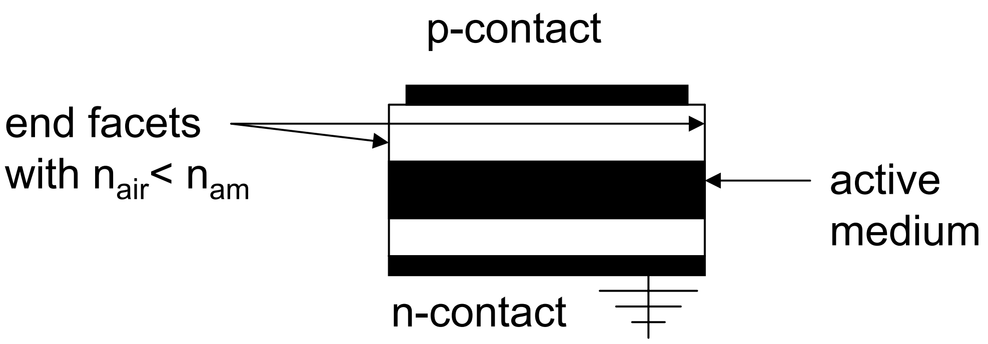

Diode laser
overgrown GaN ELOG template
'suture'
SiO$_2$ stripe mask
GaN buffer layer
sapphire substrate
threading dislocations (edge, screw, mixed)


Device Region
suture
1.0µm
seed
SiO$_2$
GaN
sapphire
1.0 µm
suture
seed
Cross section
Plan view

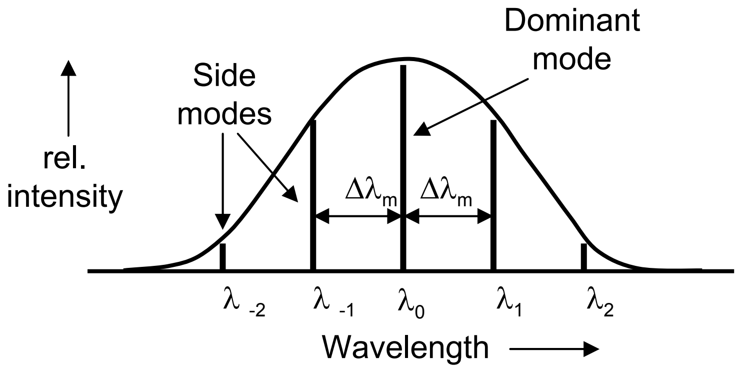
Semiconductor Laser Diode

- Introduction
- Confinement structure
- Material
- LD varieties

Fabry-Perot Laser



Spectrum



Wavelengths of the *i*th longitudinal mode

$$\lambda_i = \frac{2Ln}{i}$$

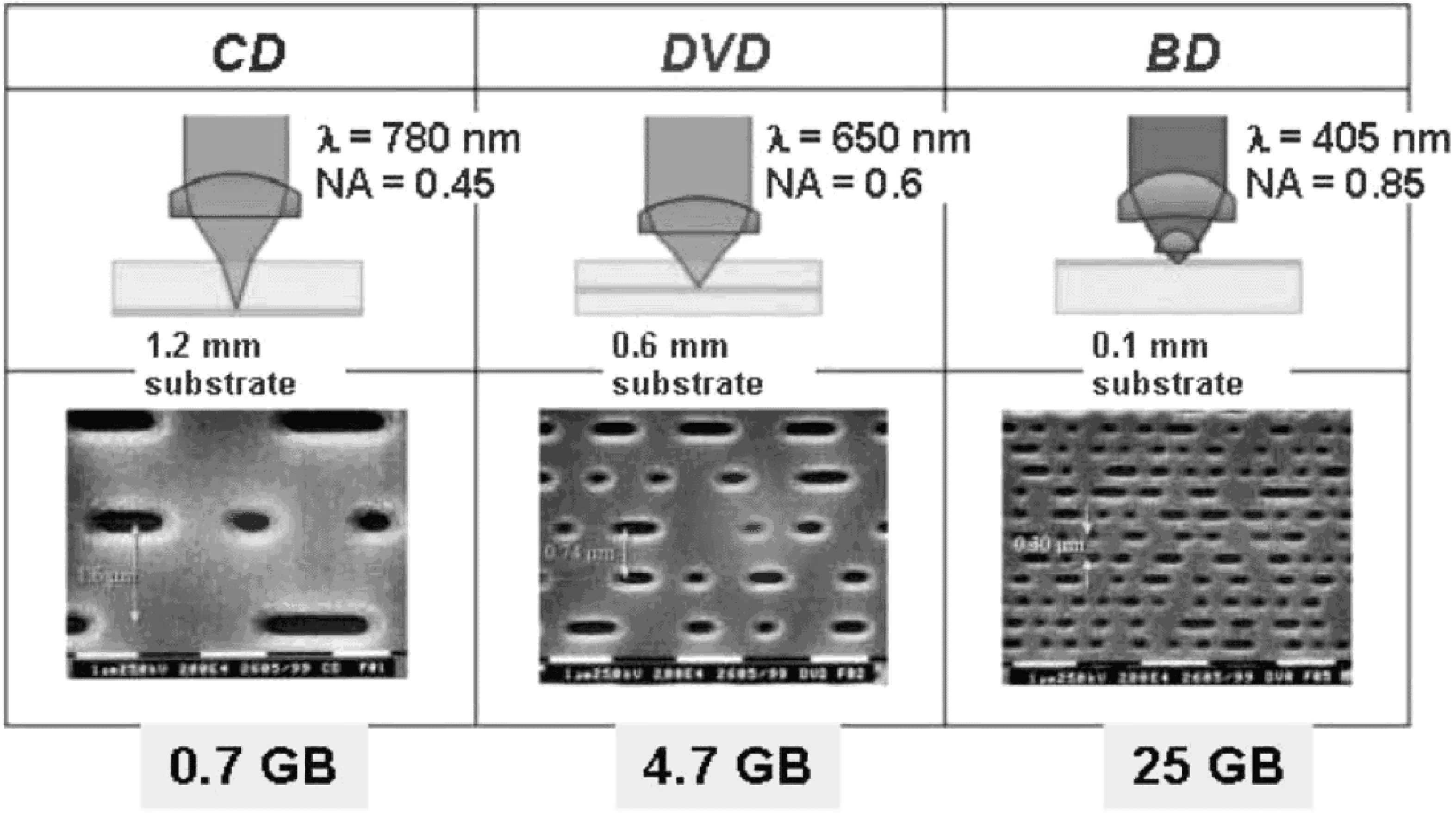
Longitudinal mode spacing

$$\Delta\lambda_m = \frac{\lambda_0^2}{2nL}$$

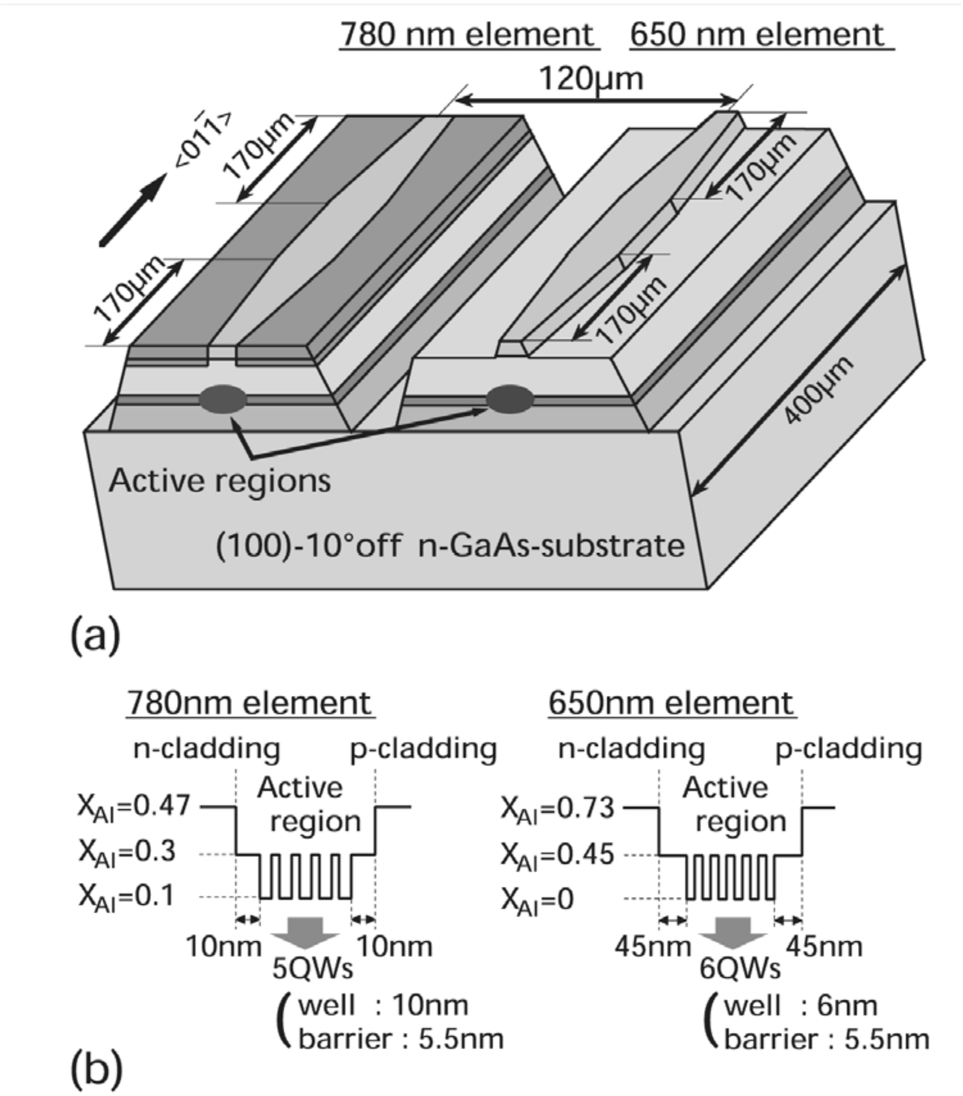
Typical value : $\Delta\lambda_m$ = 0.3 - 1 nm

光碟片 演化

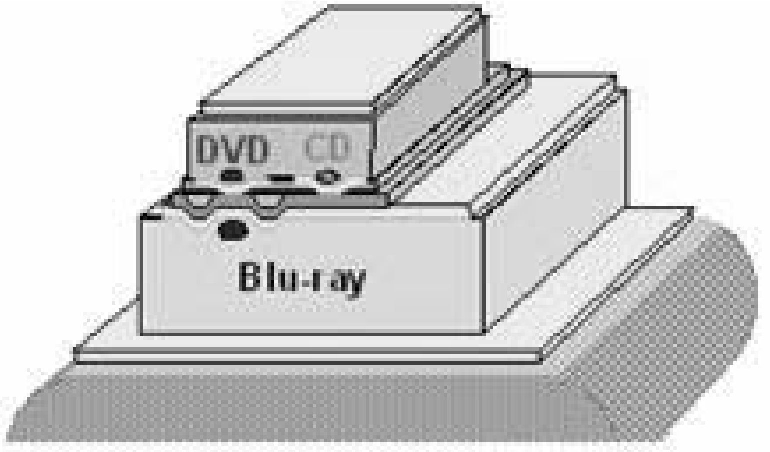
CD, DVD, BD : A Comparison

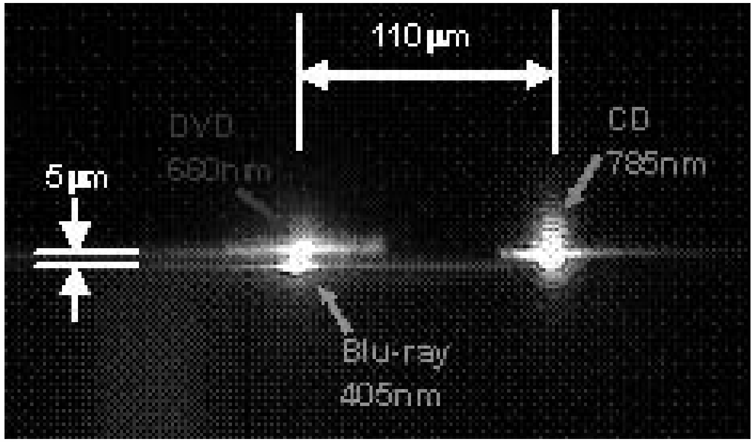


SONY Twin Waveguide Laser



SONY 三波長 LD

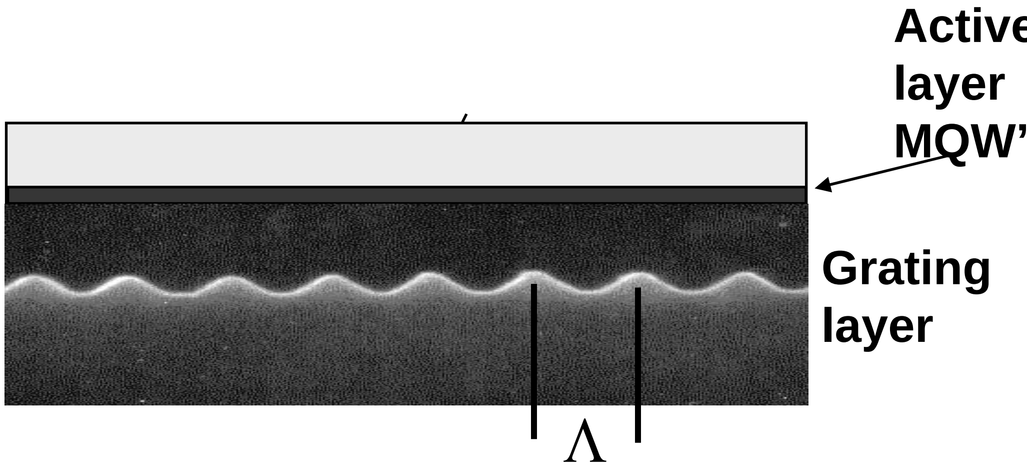


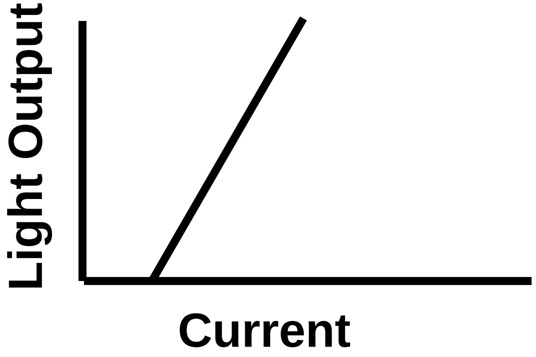


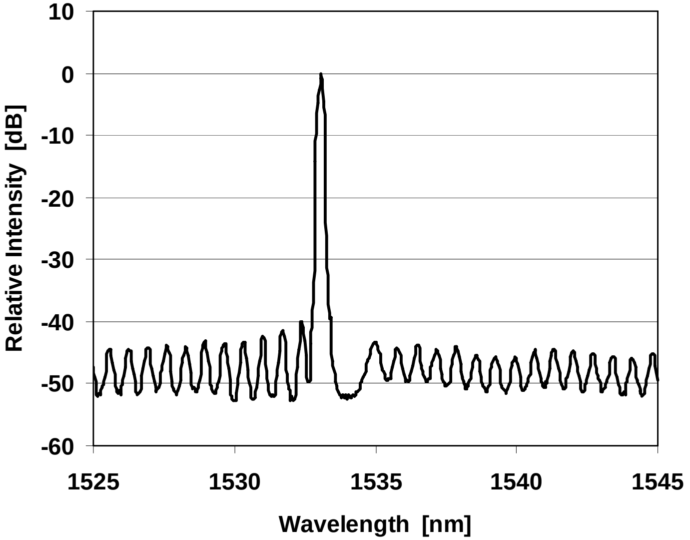
The 3 lasers will not be emitted at the same time,
when the unit is in actual use

DFB Laser

light reflected by internal grating built into laser structure



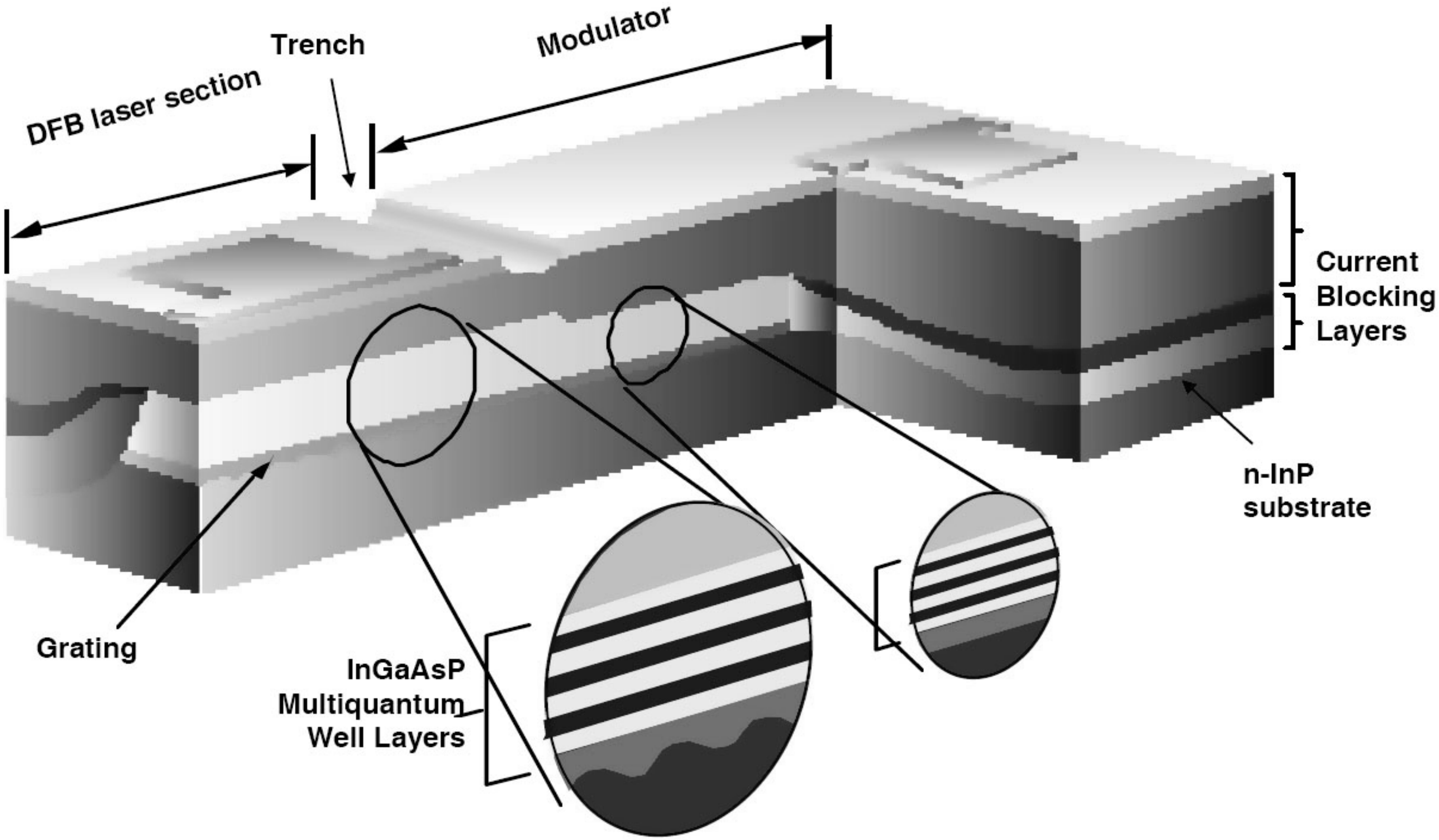




Wavelength $\lambda = 2\, n_{eff}\, \Lambda$

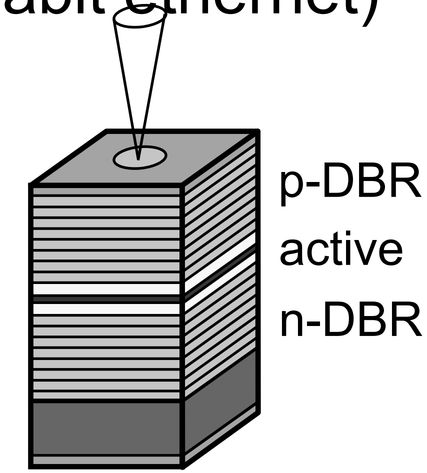
Grating period ≈ 240-245 nm !!

Electroabsorption Modulated Laser

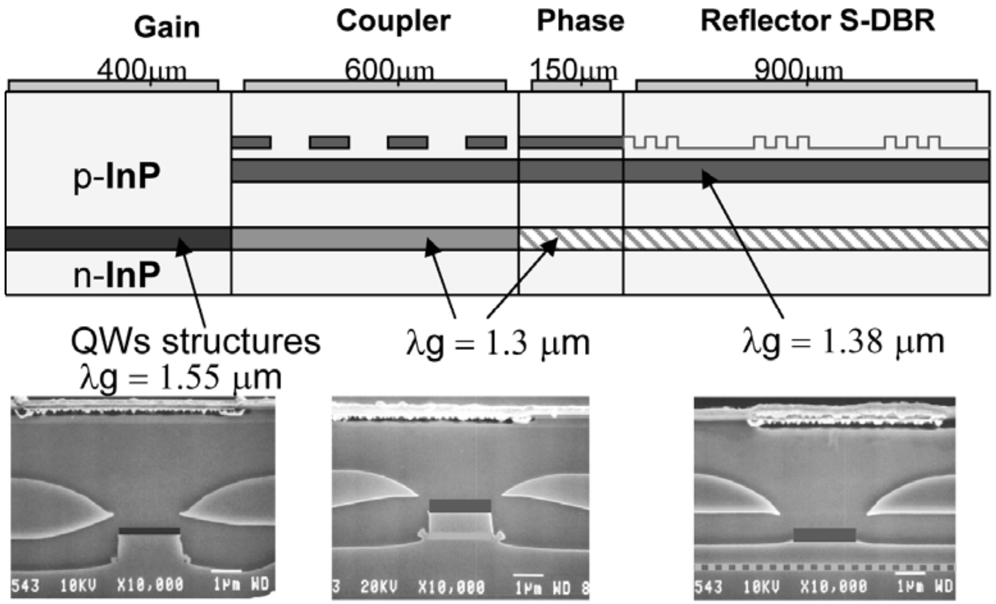


VCSEL

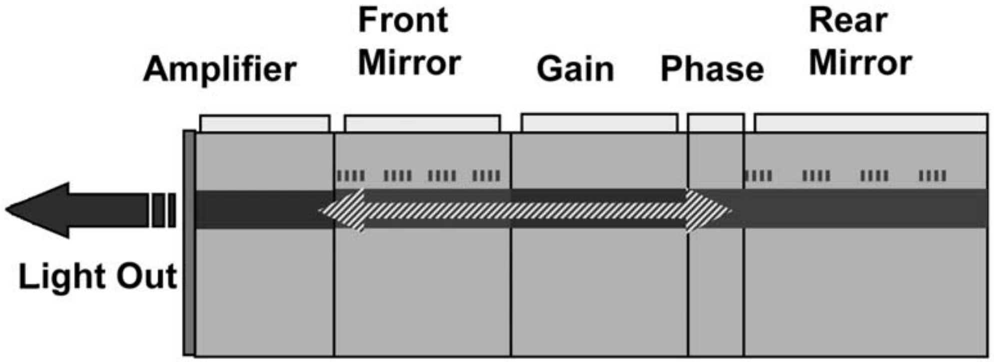
- Distributed Bragg Reflector (DBR) Mirrors
  - Alternating layers of semiconductor material
  - 40 to 60 layers, each λ / 4 thick
  - Beam matches optical acceptance needs of fibers more closely
- Key properties
  - Wavelength range 780 to 980 nm (gigabit ethernet)
  - Spectral width: <1nm
  - Total power: >-10 dBm
  - Coherence length:10 cm to 10 m
  - Numerical aperture: 0.2 to 0.3



Tunable DBR LD

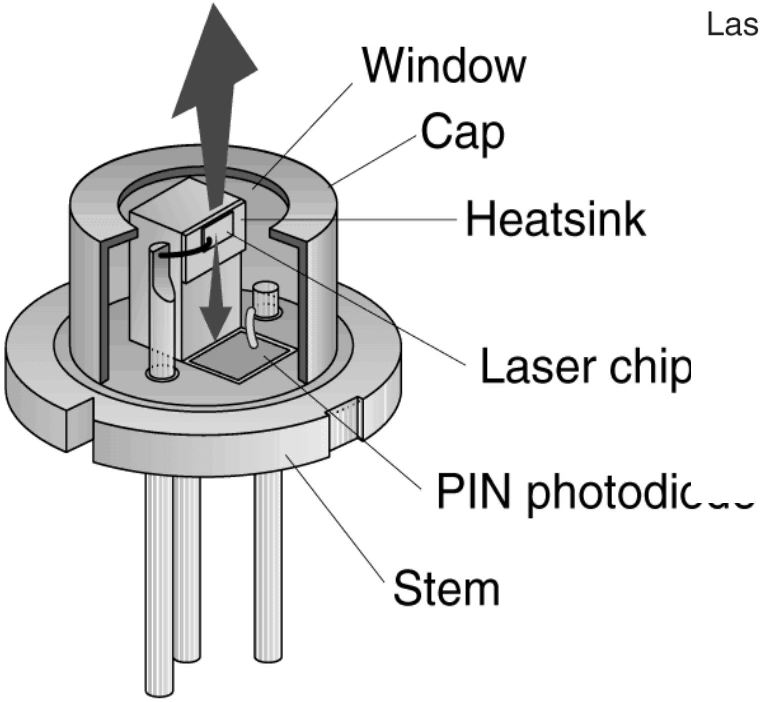


GCSR

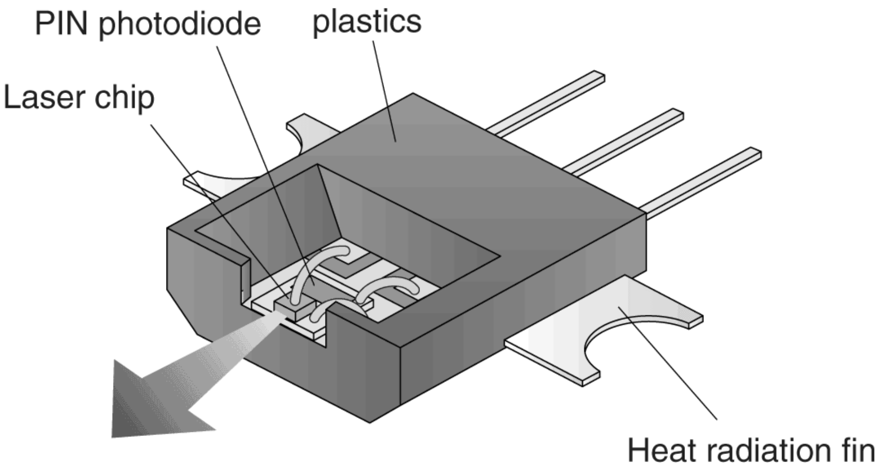


SG

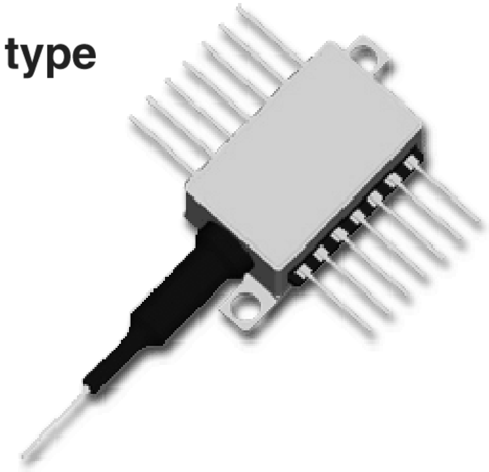
雷射二極體封裝



Can type

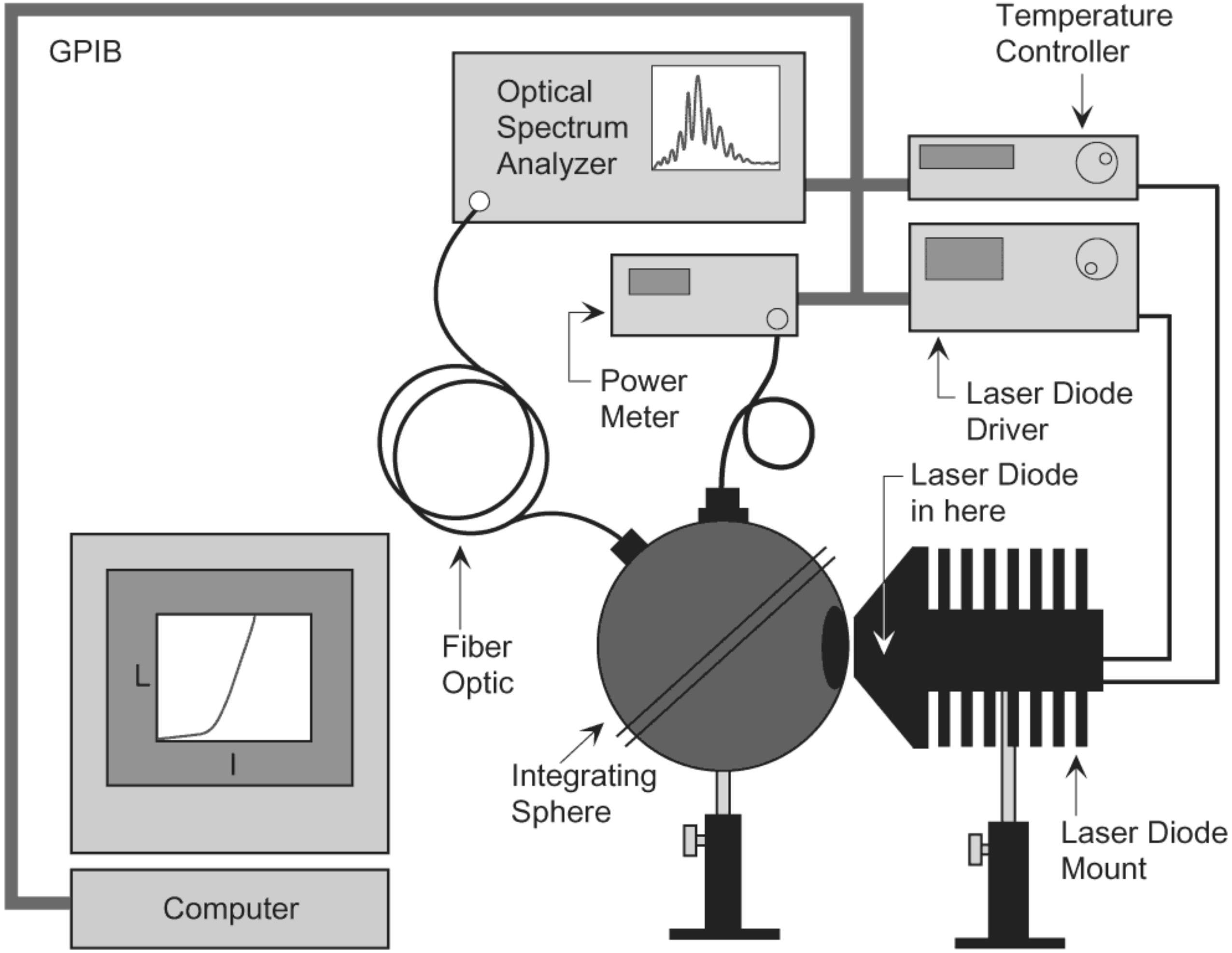


Frame type

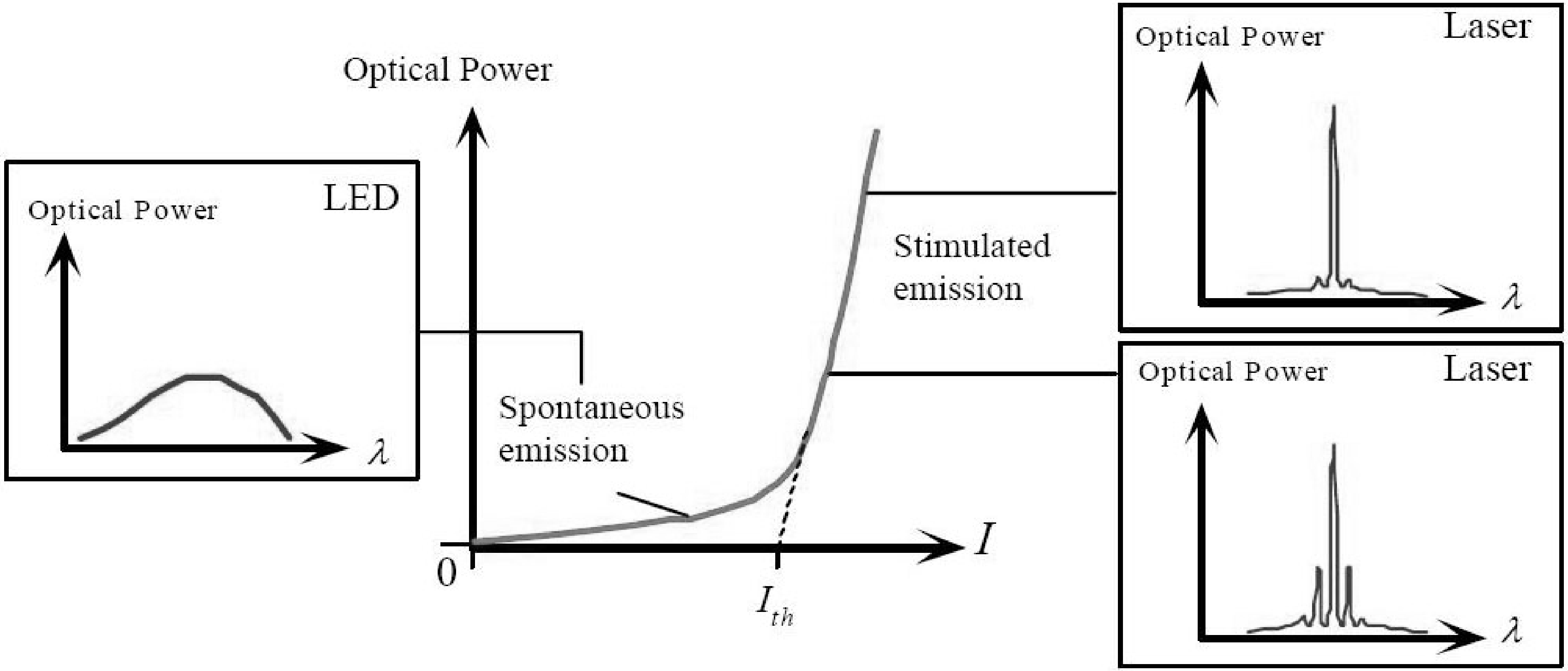


Butterfly type

LD Characterization

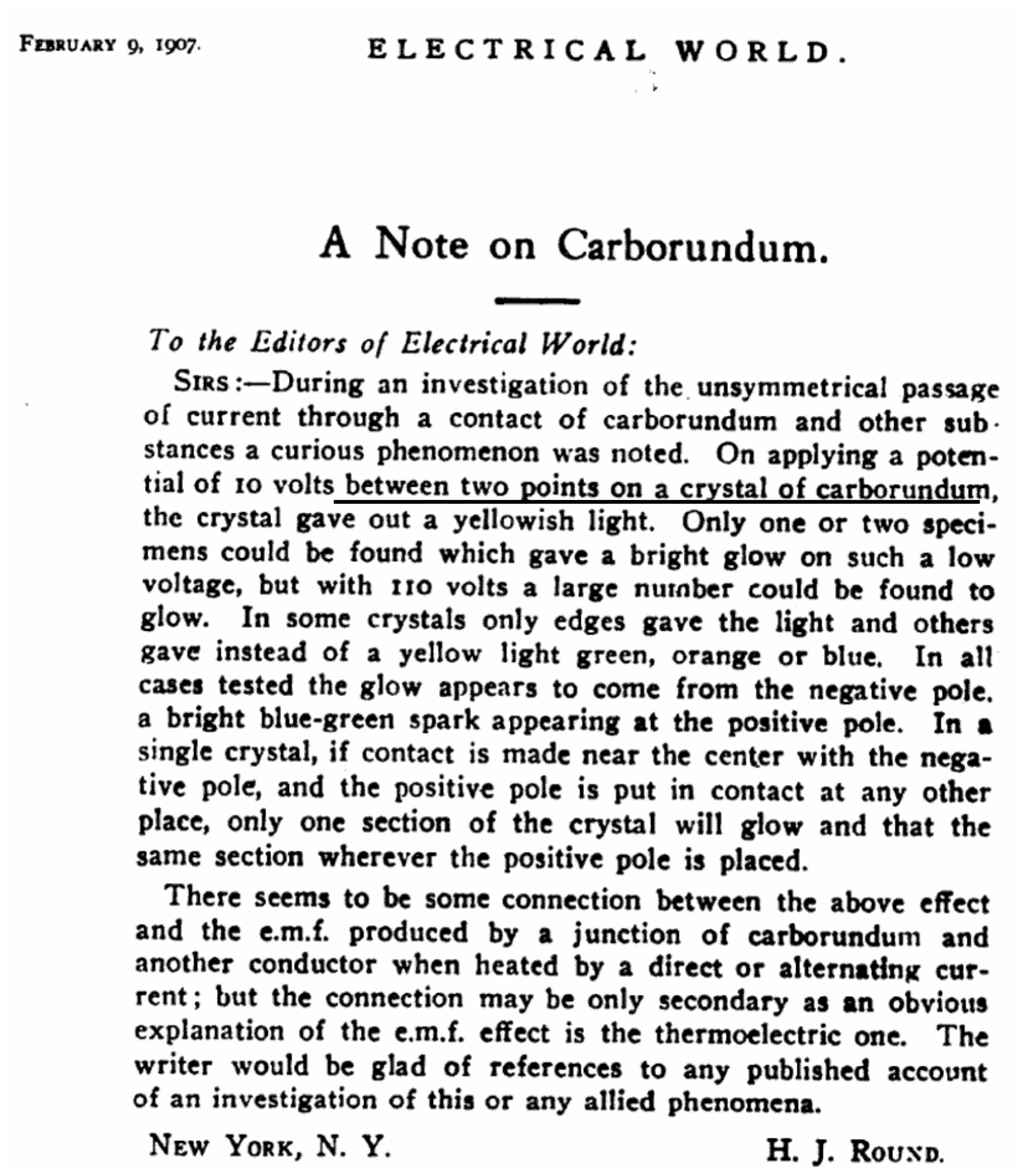


Laser Diode Output



Light Emitting Diodes

First LED (1907)



FEBRUARY 9, 1907. ELECTRICAL WORLD.

A Note on Carborundum.

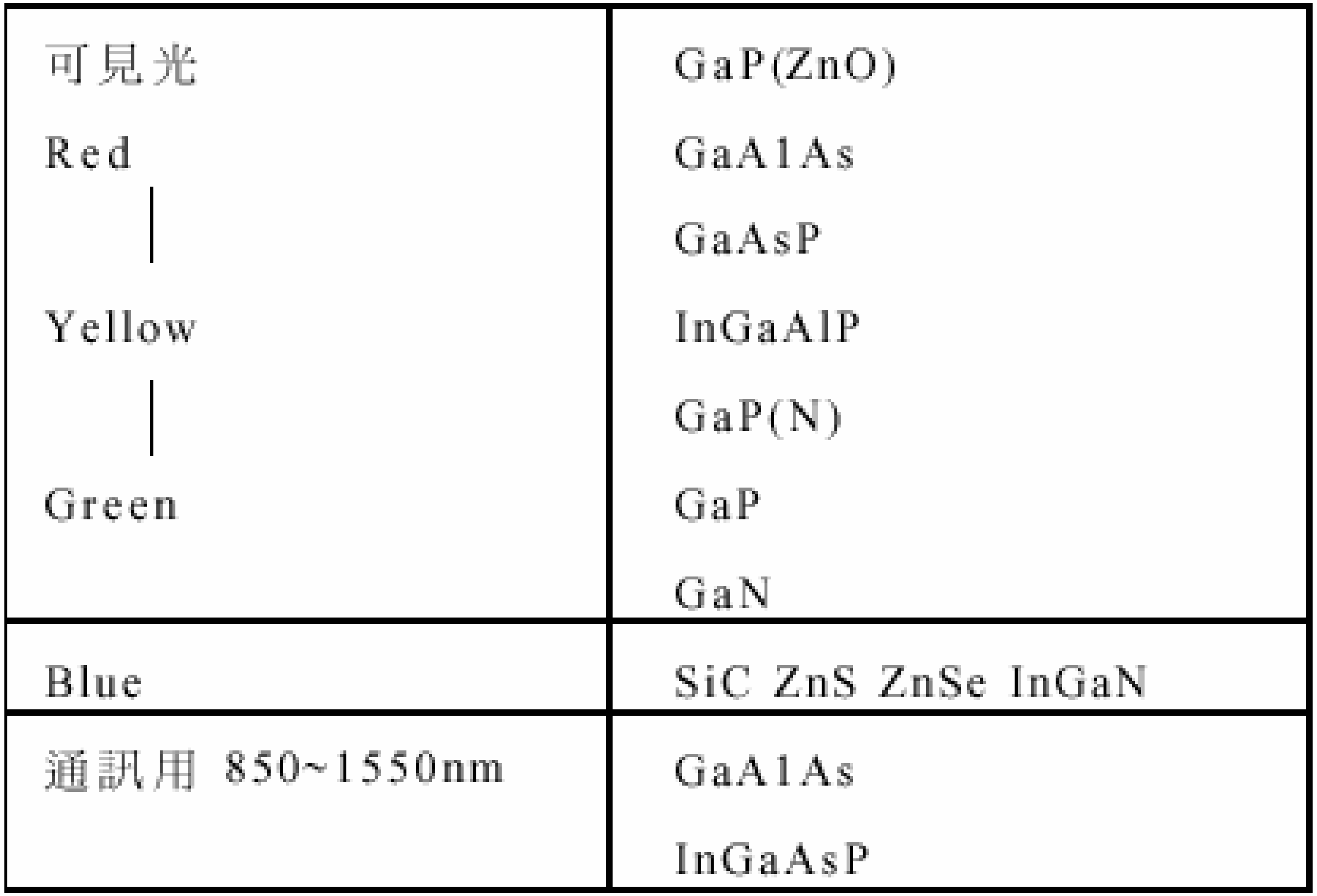
To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y. H. J. ROUND.

LED Material

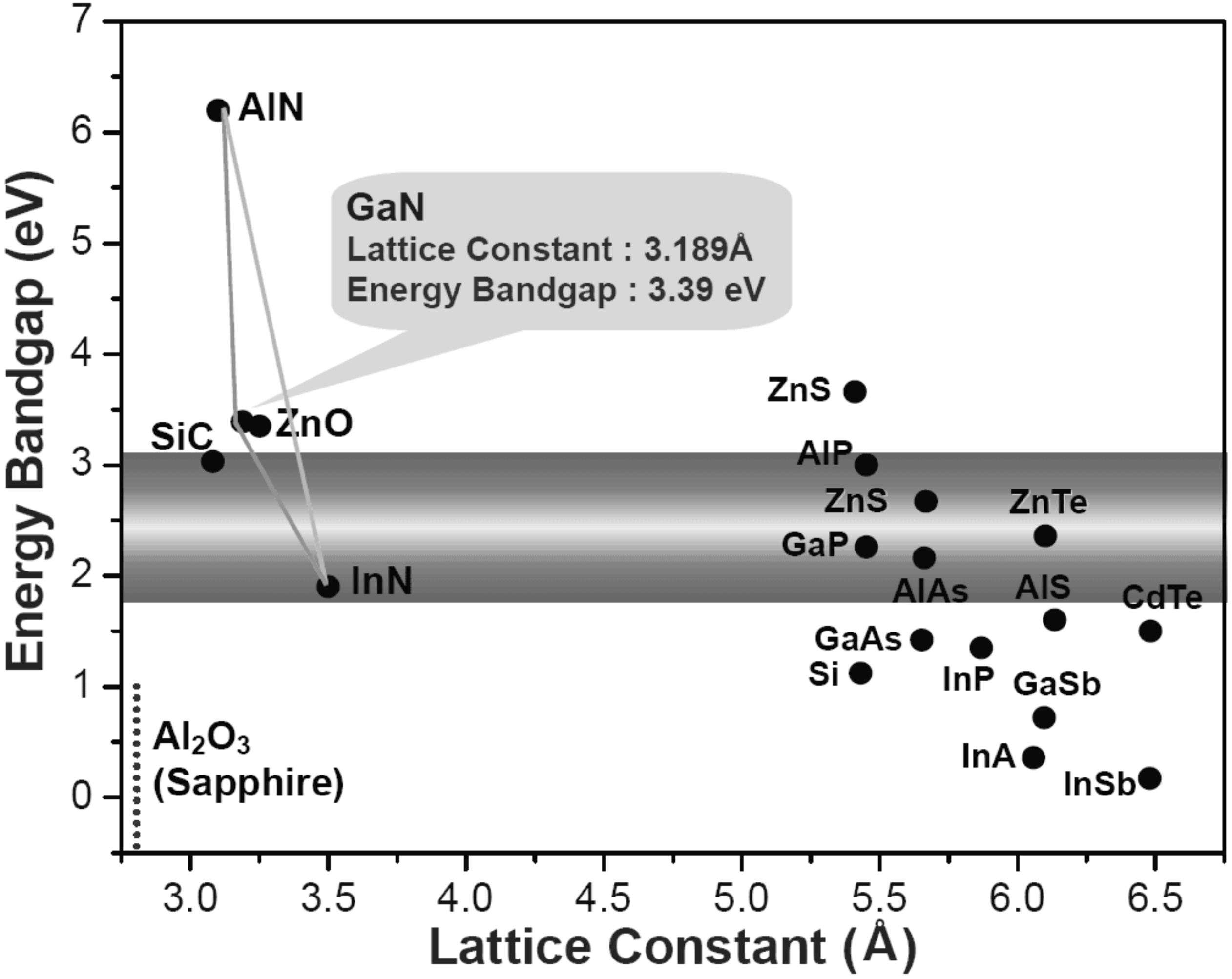


可見光 Red │ Yellow │ Green	GaP(ZnO) GaA1As GaAsP InGaAlP GaP(N) GaP GaN
Blue	SiC ZnS ZnSe InGaN
通訊用 850~1550nm	GaA1As InGaAsP

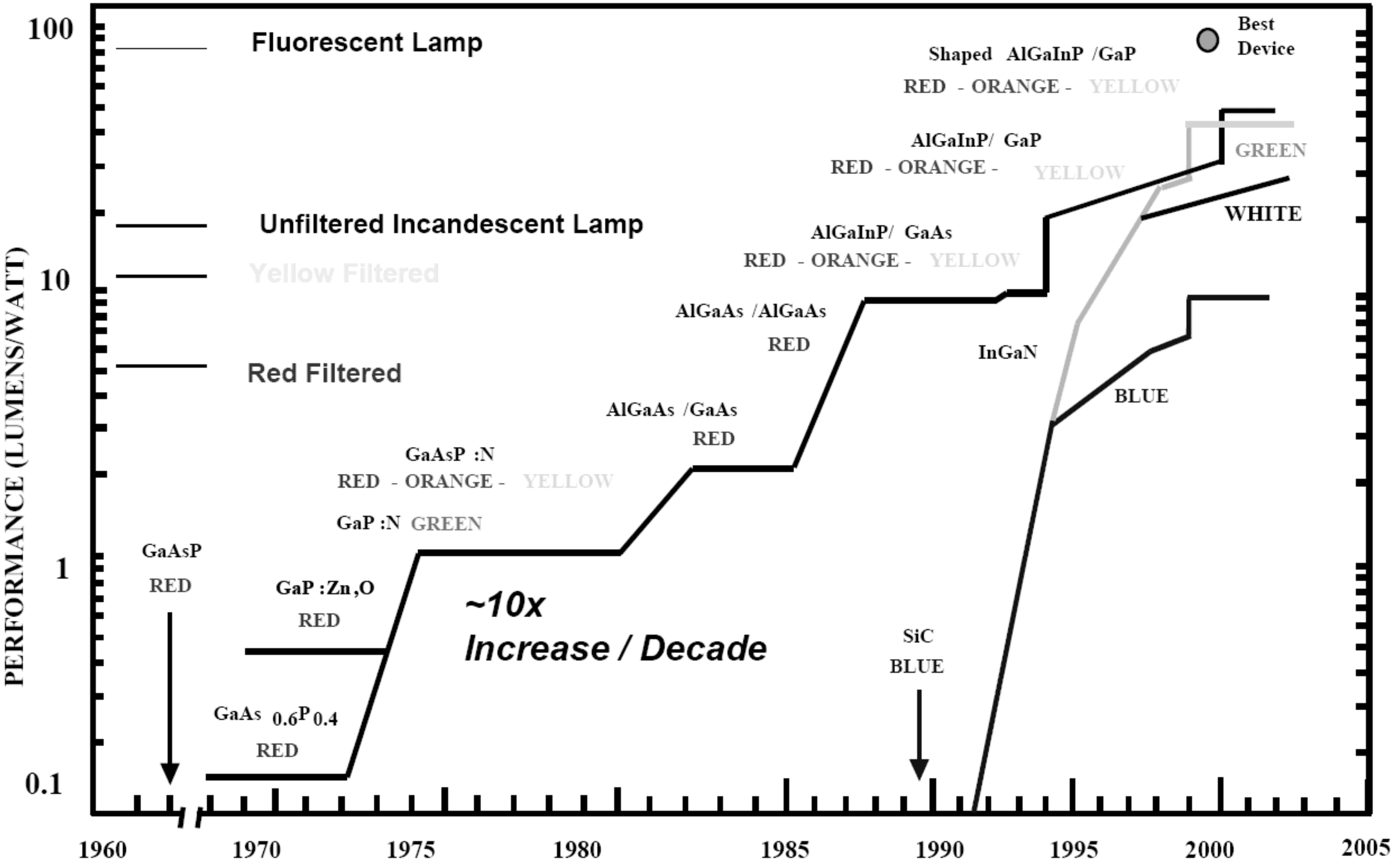
LED 磊晶與分類

亮度	磊晶方法	基板	發光層材料	產品顏色與波長
高亮度	MOCVD	Sapphire	GaN	綠光520nm, 藍光465 nm
	MOCVD	GaAs	AlGaInP	紅光635nm、紅橙光620nm、黃光590nm
中低亮度	LPE	GaAs	AlGaAs	紅光655nm
	VPE +擴散	GaP	GaAsP	紅光650nm、橙光630nm、黃光585nm、黃綠光565/555nm
	LPE	GaP	GaP	紅光700nm

GaN Material

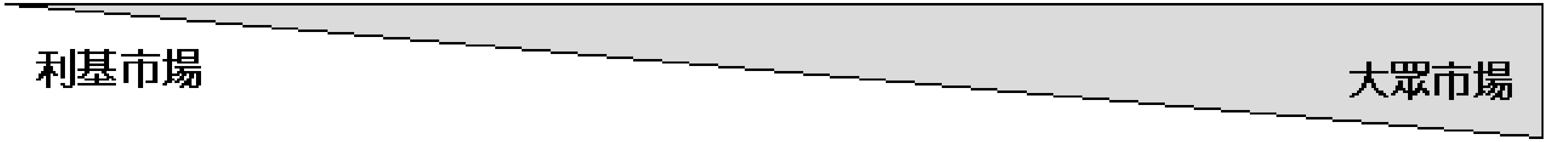


LED在波長及亮度之演進

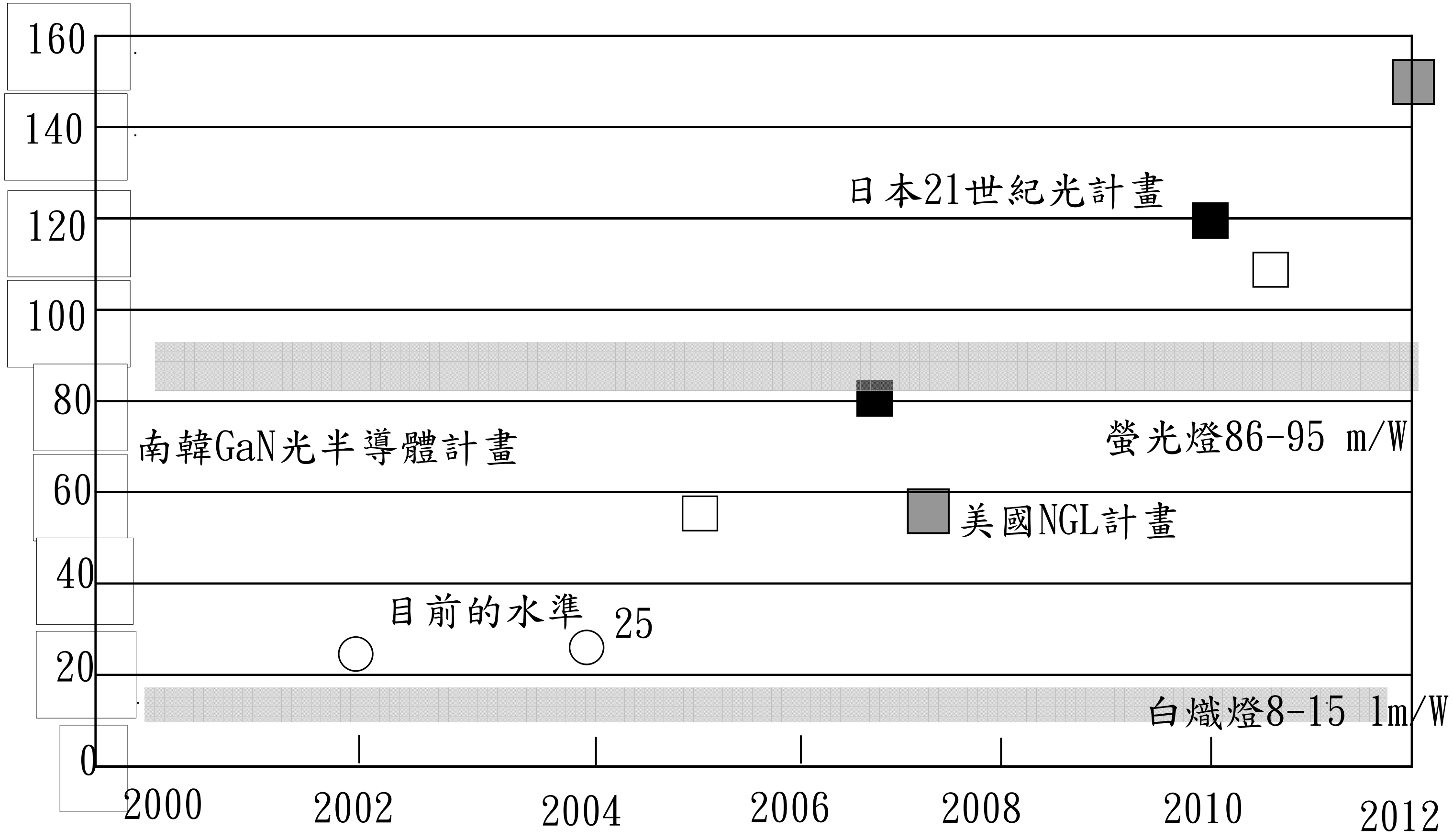


LED Market Evolution

1960	1970	1980~5	1986~9	1990	1993	1997	2001	Future
GaAsP Red LED	GaAsP 高效率 Red LED & yellow LED GaP Green & Red LED	GaAlAs Orange ,Yellow Green, & Red LED	InGaAlP Orange ,Yellow Green, & Red LED 以高亮度與 高可性賴度 為目標	InGaAlP 使用MOCVD 製程使得亮度 增加兩倍， Orange-red, Orange, Yellow & Green LED	GaN Blue LED InGaN 高飽和度 Green & Blue LED	InGaN + YAG 螢光粉 =**White LEDs** (使用Blue LED 當激發光源)	InGaN + GGB3波長 螢光粉 =**White LEDs** (使用UV LED 當激發光源)	1.美國固態光專案 2.日本21世紀照明 發展第二期計畫 3.歐盟彩虹計畫 主要目標都是強化 LED 發光效率，節 省能源為主
指示燈	計算機 數位手錶 測試儀器	戶外訊號 Bar Code 光纖傳輸系統 醫療儀器	戶外看板	交通控制訊號 訊息顯示看板 汽車	醫療診斷 設備 照相平板 印刷設備	小尺寸LCD背光源 全彩大螢幕看板 行動電話按鍵 汽車內燈光 裝飾燈		彩色手機面板 汽車前燈照明 LCD TV背光源 民生照明

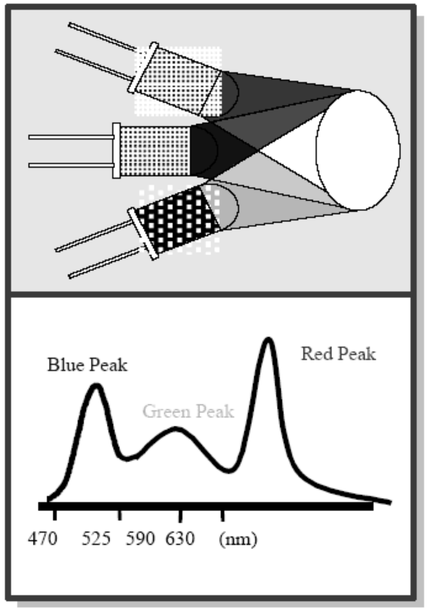


白光LED發光效率預測表



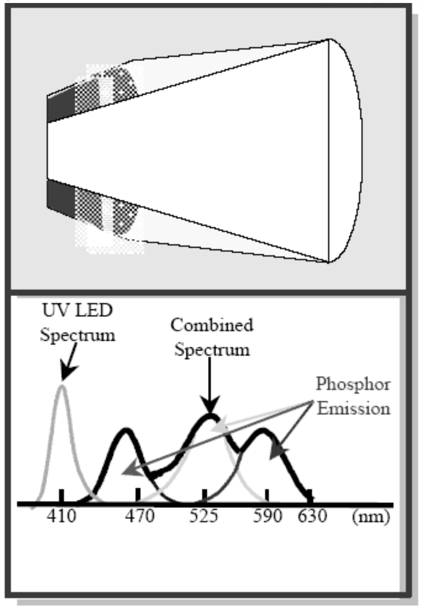
產生白光之方法

Red + Green + Blue LEDs



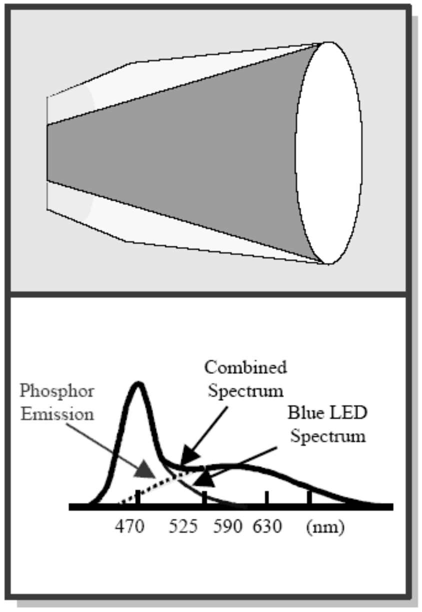
- Dynamic color tuning
- Excellent color rendering
- Large color gamut

UV LED + RGB Phosphor



- White point tunable by phosphors
- Excellent color rendering
- Simple to create white

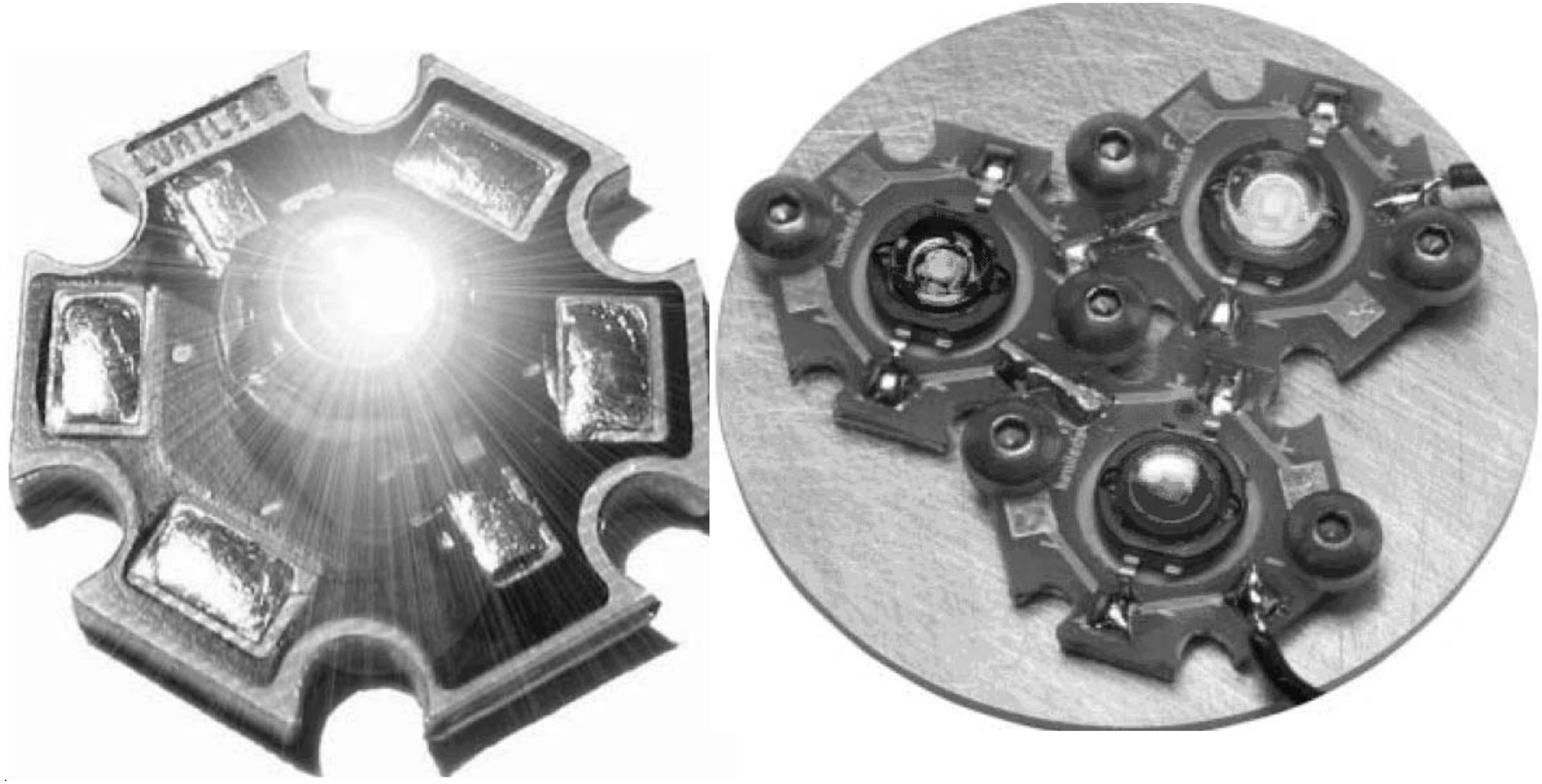
Blue LED + Yellow Phosphor



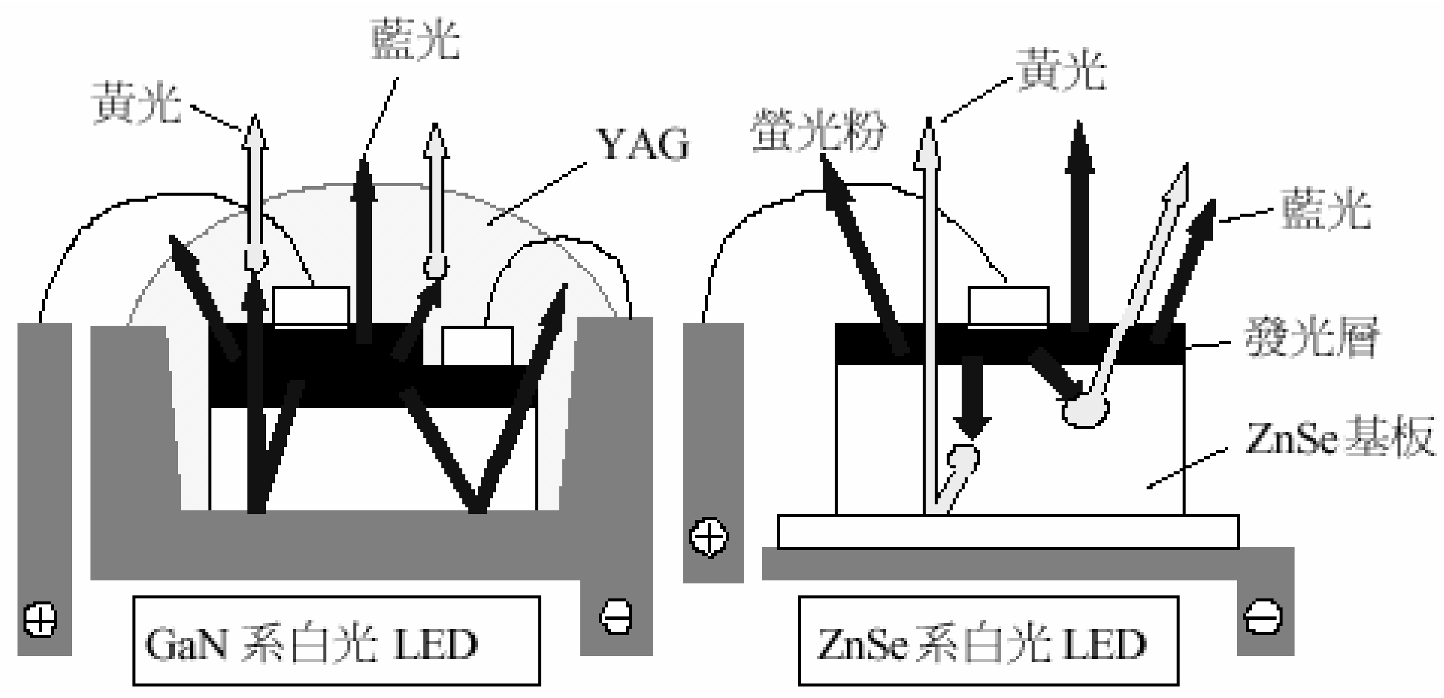
- Simple to create white
- Good color rendering

There are various ways to create white light from LEDs, each with specific advantages.

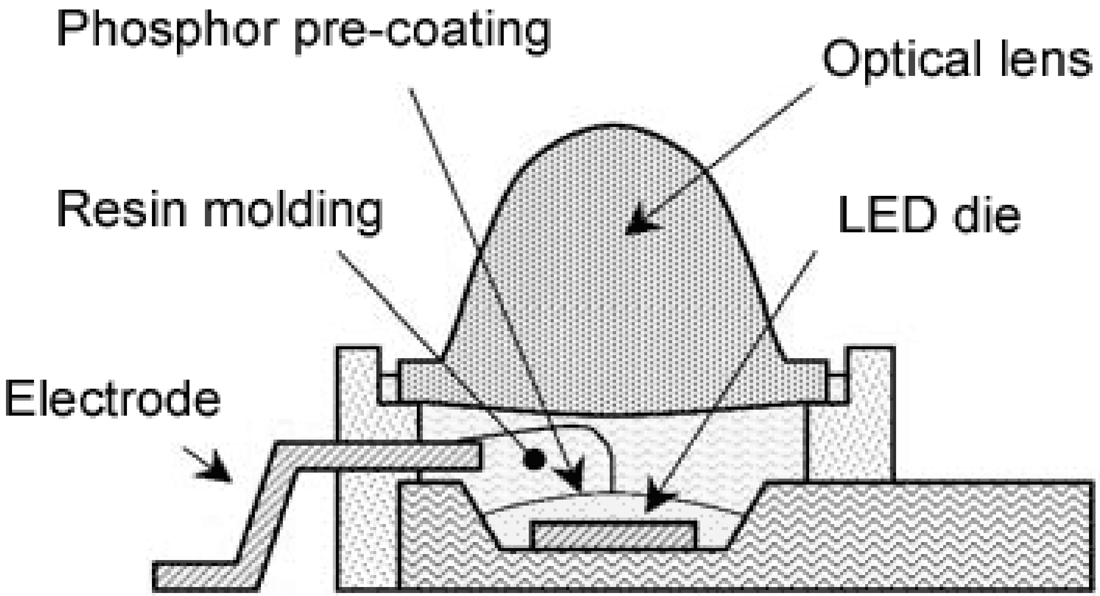
Lumiled Luxeon



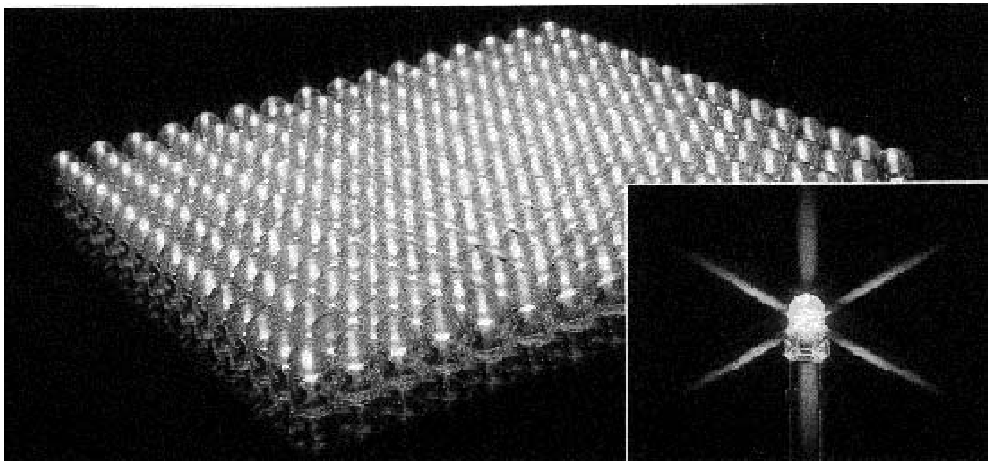
產生白光之方法



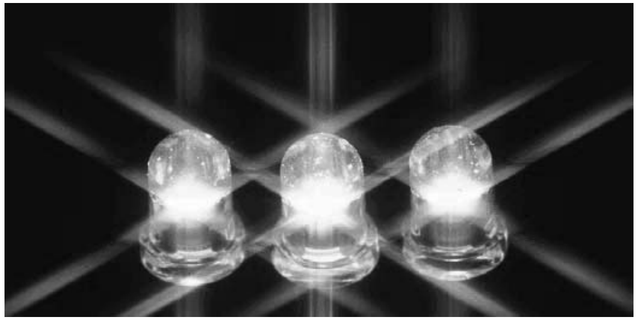
Nichia White LED Structure



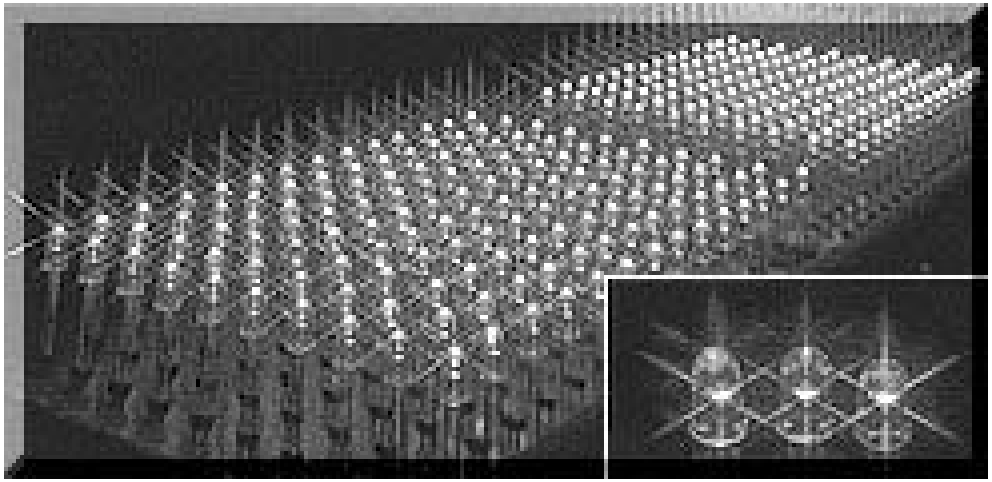
Nichia GaN LEDs



White

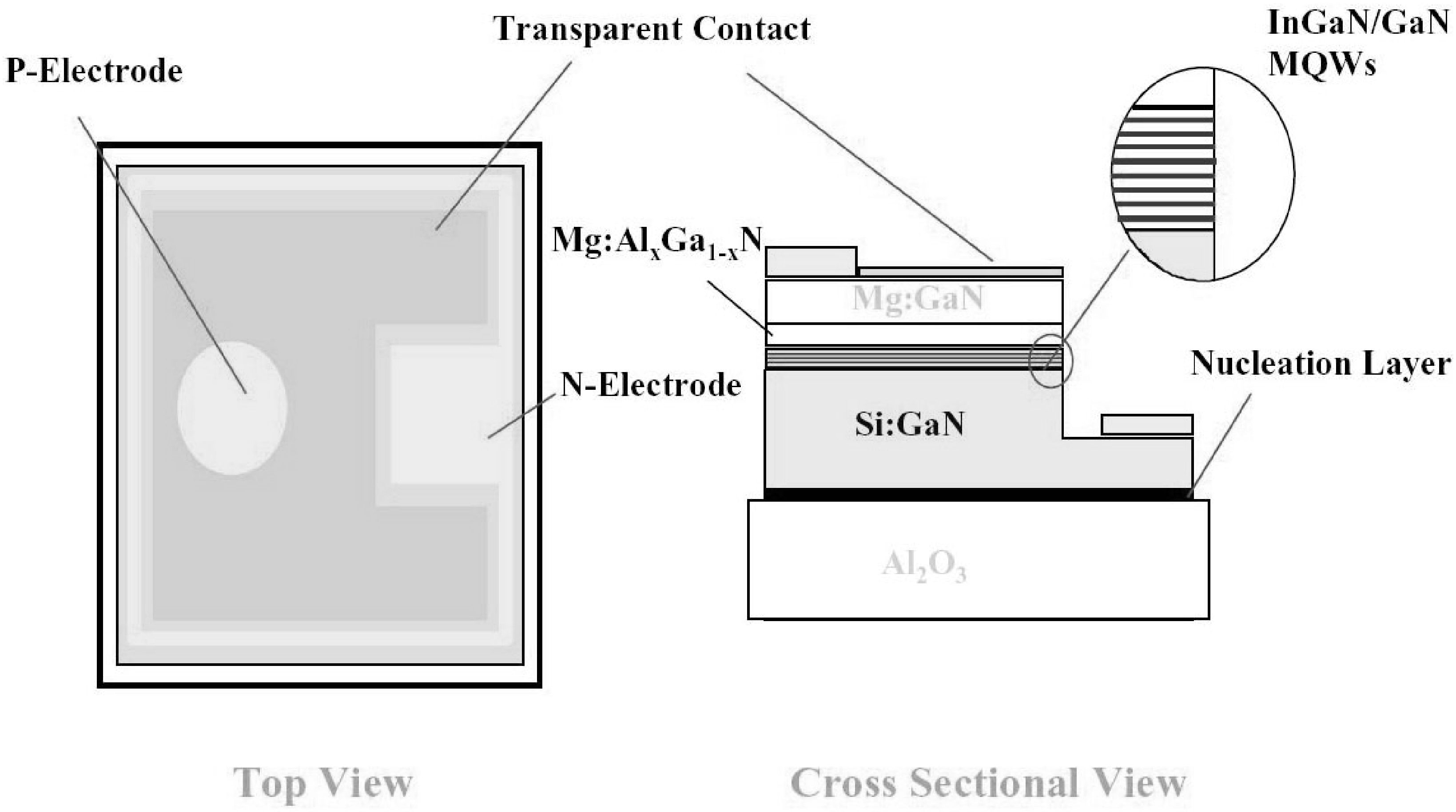


Warm White

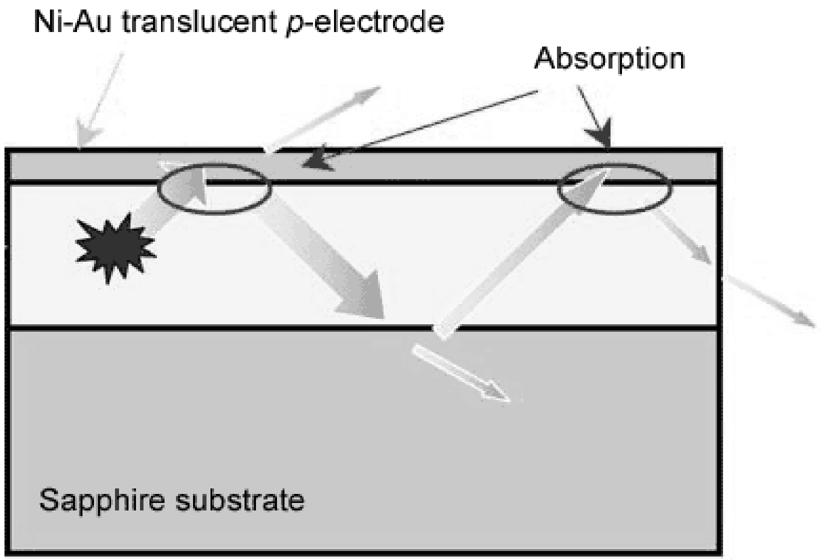


Blue

Typical GaN LED

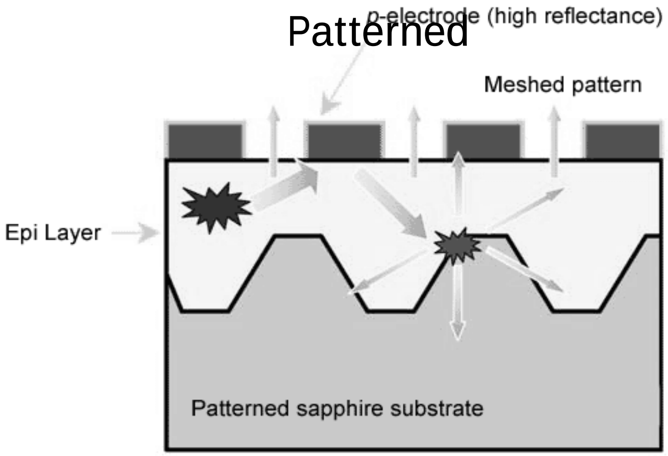


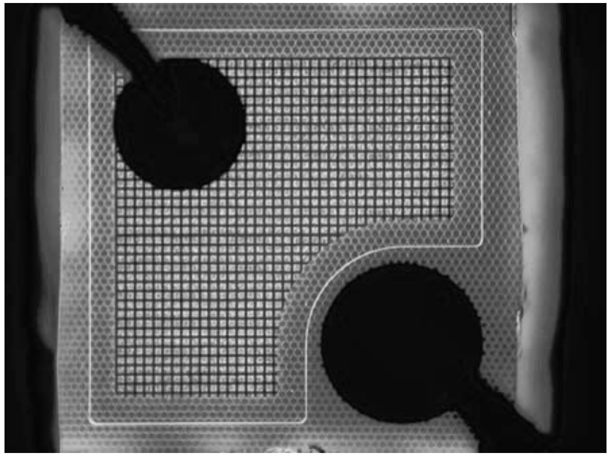
Patterned Substrate and Electrode



Conventional

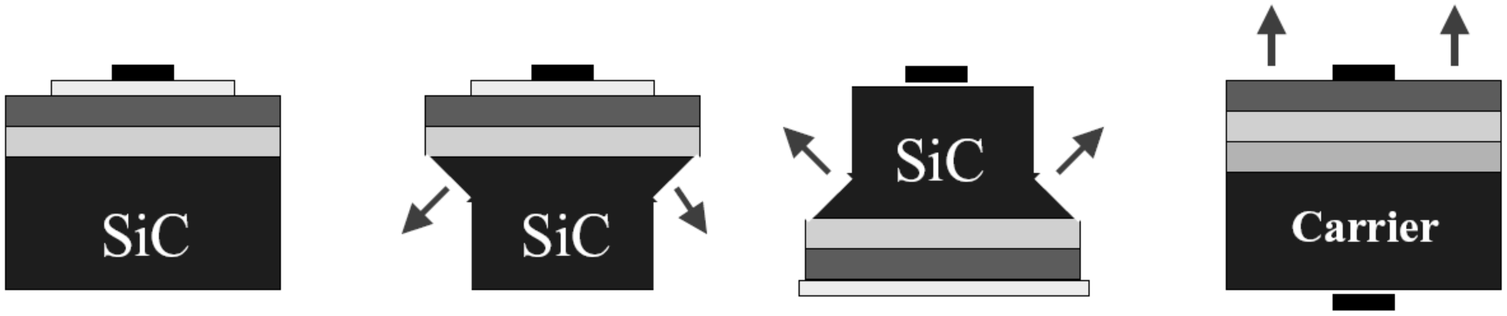
Patterned





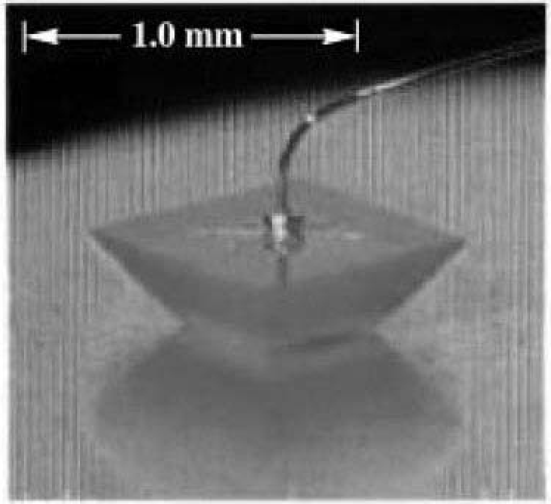
Light Extraction

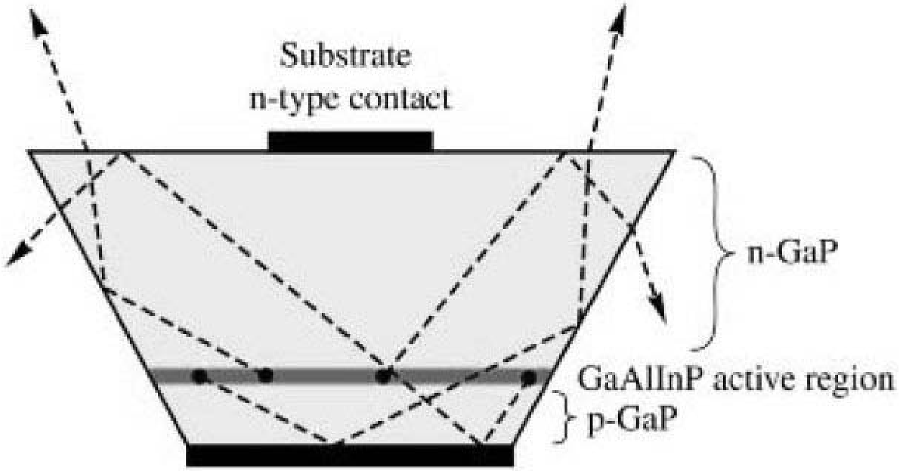
OSRAM



Standard	ATON	NOTA	ThinGaN
25%	52%	60%	75%

Chip Shaping

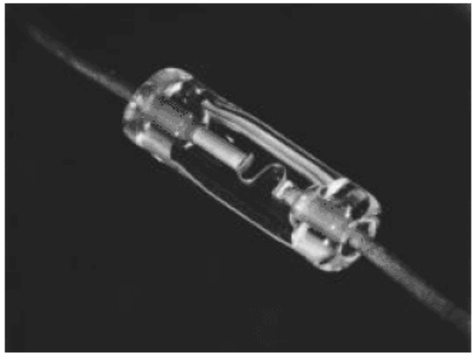




M. R. Krames et al., Appl. Phys. Lett. 75, 2365 (1999).

LED 封裝技術演化

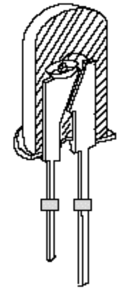
- **Power LEDs can handle ~50x power of an Indicator LED!**



1962

First Packaged LED

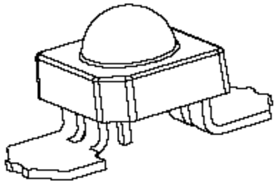
Indicator LED



P_{max}~0.1W
150-200 K/W
1970

Standard 5mm Lamp

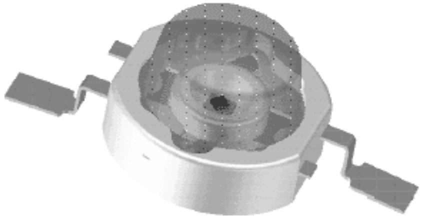
Indicator LED



P_{max}~0.2-0.4W
50 K/W
1994

LumiLeds SnapLED™

First Power LED



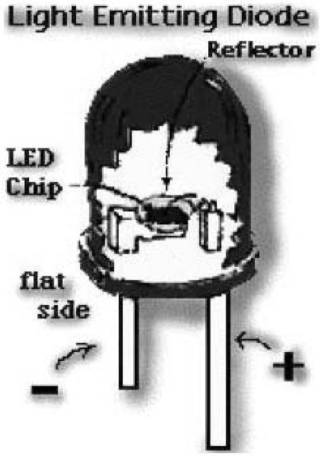
P_{max}~0.6-4.0W
9-14 K/W
1998

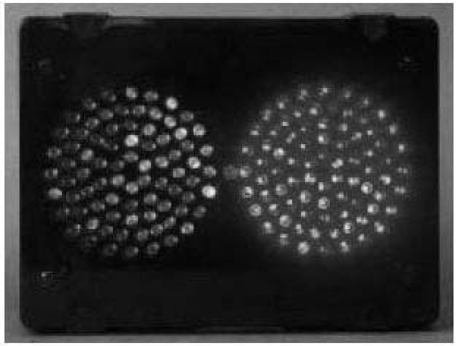
LumiLeds Luxeon™

Today's Power LED

From LUMILEDS

Light Emitting Diode



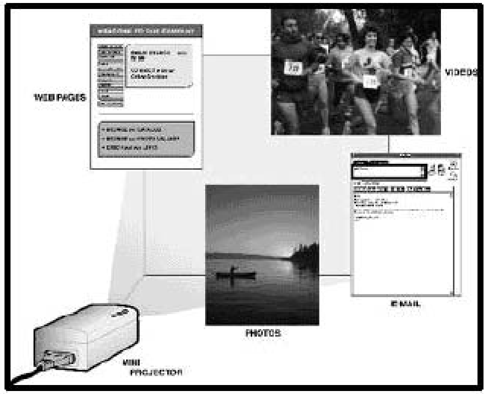


- Bright, sunlight readable
- Displays video, animation, graphics, text
- Runs MPEG (1 & 2), AVI
- Video sources: DVD, S-Video, Hard drive, VHS, Betacam, Cable, Satellite, Camera
- Network ready, Remote control
- Easy to use operating software
- Low power consumption
- Low maintenance costs
- Low price

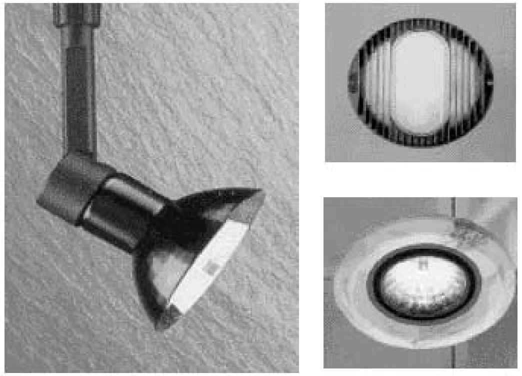
- 16,7 million colours
- Resolutions:

Emerging LED Markets

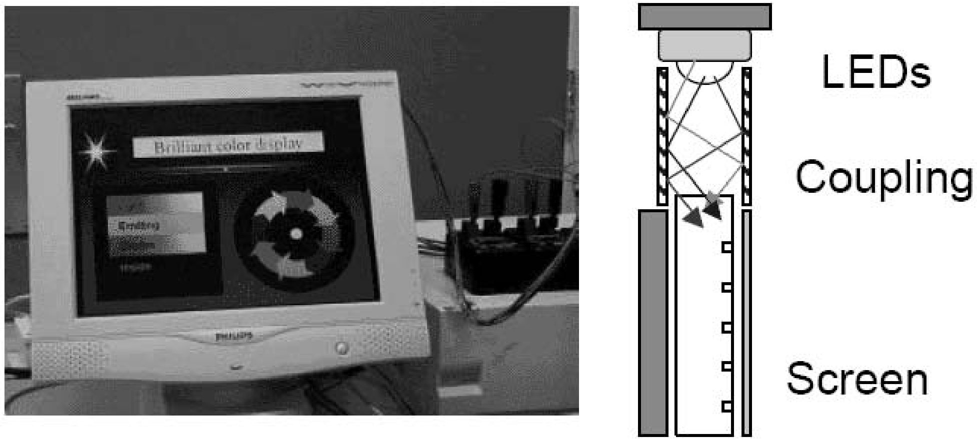
Flashlights



Mini Projection Displays



Accent Lighting



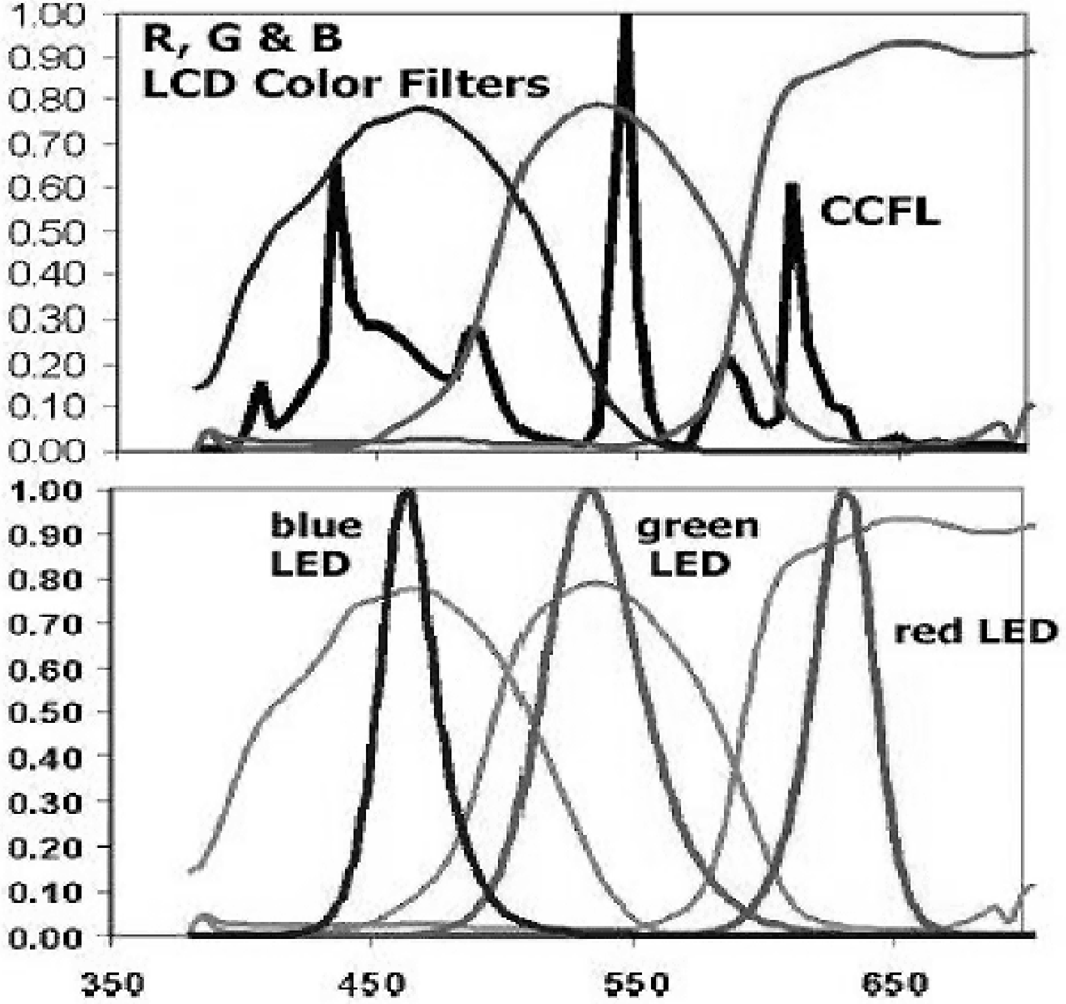
18” LCD monitor with LED backlight

LCD 背光應用

Features of LED Backlights

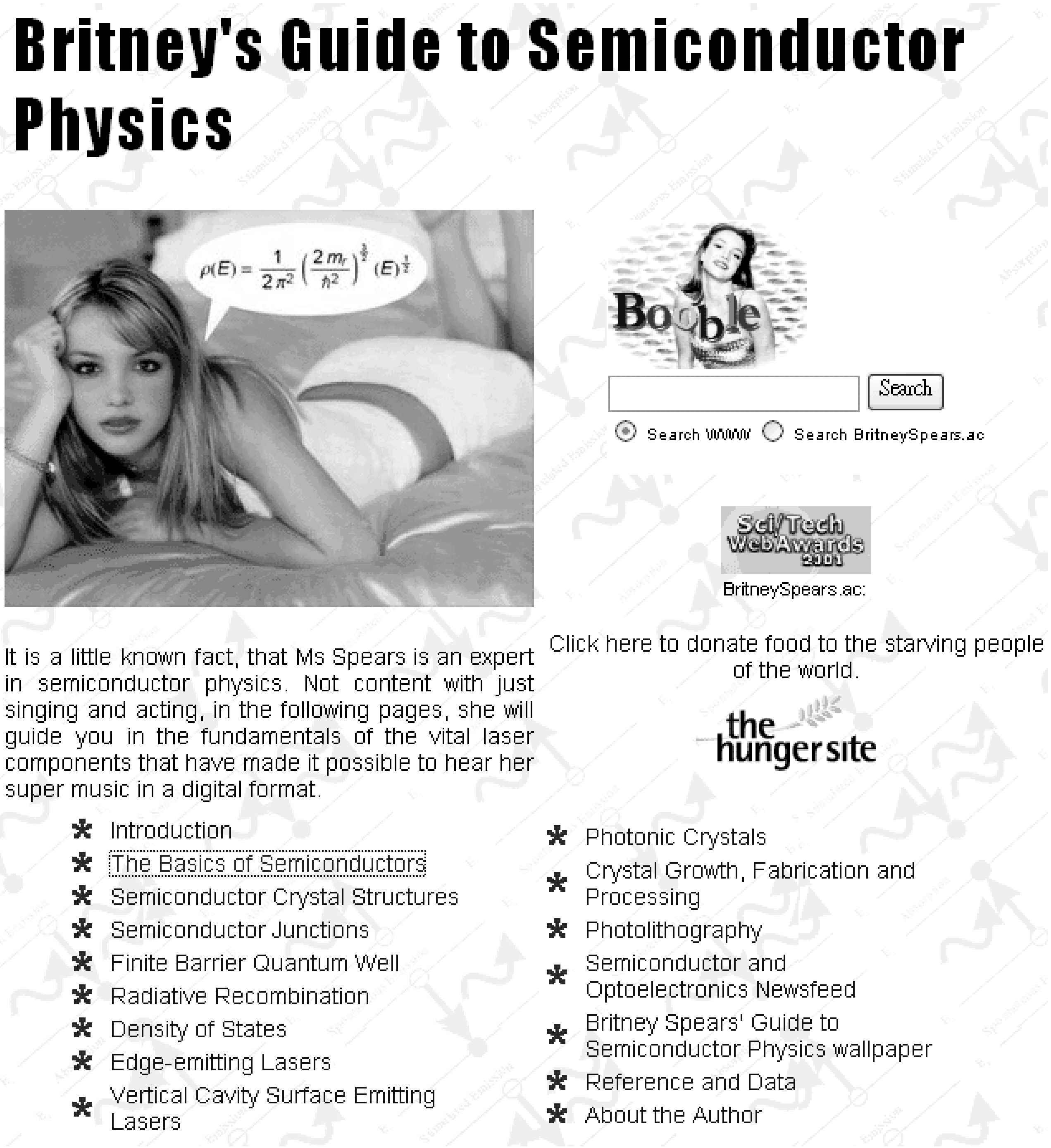
- No mercury and 50,000~100,000 hr life
- Increased Color Gamut using standard color filters
- (Dynamic) White point adjustment in back light
- Eventually, reduced energy consumption

Spectrum Comparison



全球主要LED廠商

	上游	中游	下游
日本	Nichia、Rohm		
	Toyoda-Gosei		Citizen、Stanley、Kagoshima、Toshiba
美國及歐洲	Osram、Lumileds		
	Cree、AXT、GelCore、Uniroyal		Agilent
韓國	Samsung、LG		
台灣	國聯、晶元、璨圓、元砷、華上 廣稼、洲磊、晶專、連勇、南亞		光寶、億光、佰鴻 東貝、華興、光鼎 瑩寶、恆嘉、今台 先益、立碁、琭旦 李洲、興華、詮興 宏齊
	信越、全新、連威 興光、聯亞	光磊、鼎元 漢光	
周邊材料	**導線架** 一詮、大鐸、尚品	**金線** 九介、庫利、索法	**環氧樹脂及銀膠餅** 日東、宜加、至鴻



Britney's Guide to Semiconductor Physics

BritneySpears.ac:

Click here to donate food to the starving people of the world.

It is a little known fact, that Ms Spears is an expert in semiconductor physics. Not content with just singing and acting, in the following pages, she will guide you in the fundamentals of the vital laser components that have made it possible to hear her super music in a digital format.