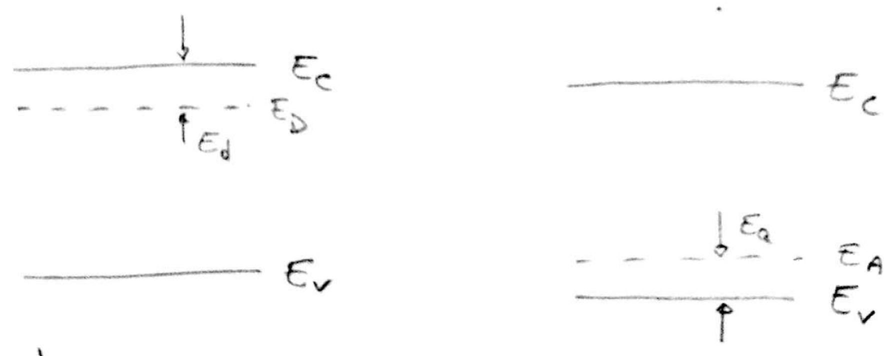
SEMICONDUCTOR HETEROSTRUCTURES

Doped Semiconductors

The intrinsic carrier concentration of a semiconductor like Si,

$$n_i = 1.5 \times 10^{10} \ \text{cm}^{-3} \qquad (\text{at } 300\text{K}),$$

is not nearly large enough to yield the current densities for practical semiconductor devices. Concentrations that are order of magnitude higher than n_i can be created by doping, i.e., by the addition of electrically active impurities to the crystal.



Donor ionization energy

$$E_d = \frac{m_e^*}{m} \frac{1}{\epsilon^2} \times 13.6 \ \text{eV}$$

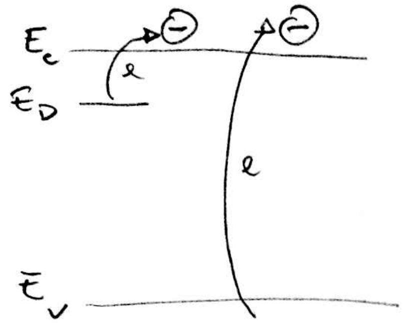
At 300K

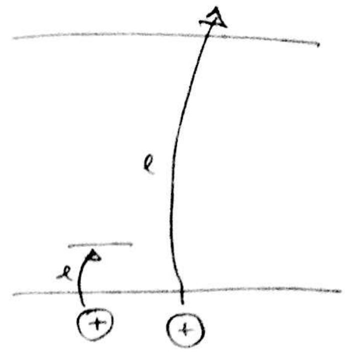
Si : $\epsilon = 11.7$; $\frac{m_e}{m} = 0.2$; $E_g = 1.1$ eV ; $E_d(P) = 0.045$ eV

GaAs : $\epsilon = 13.2$; $\frac{m_e}{m} = 0.067$; $E_g = 1.42$ eV ; $E_d(Si) = 0.005$ eV

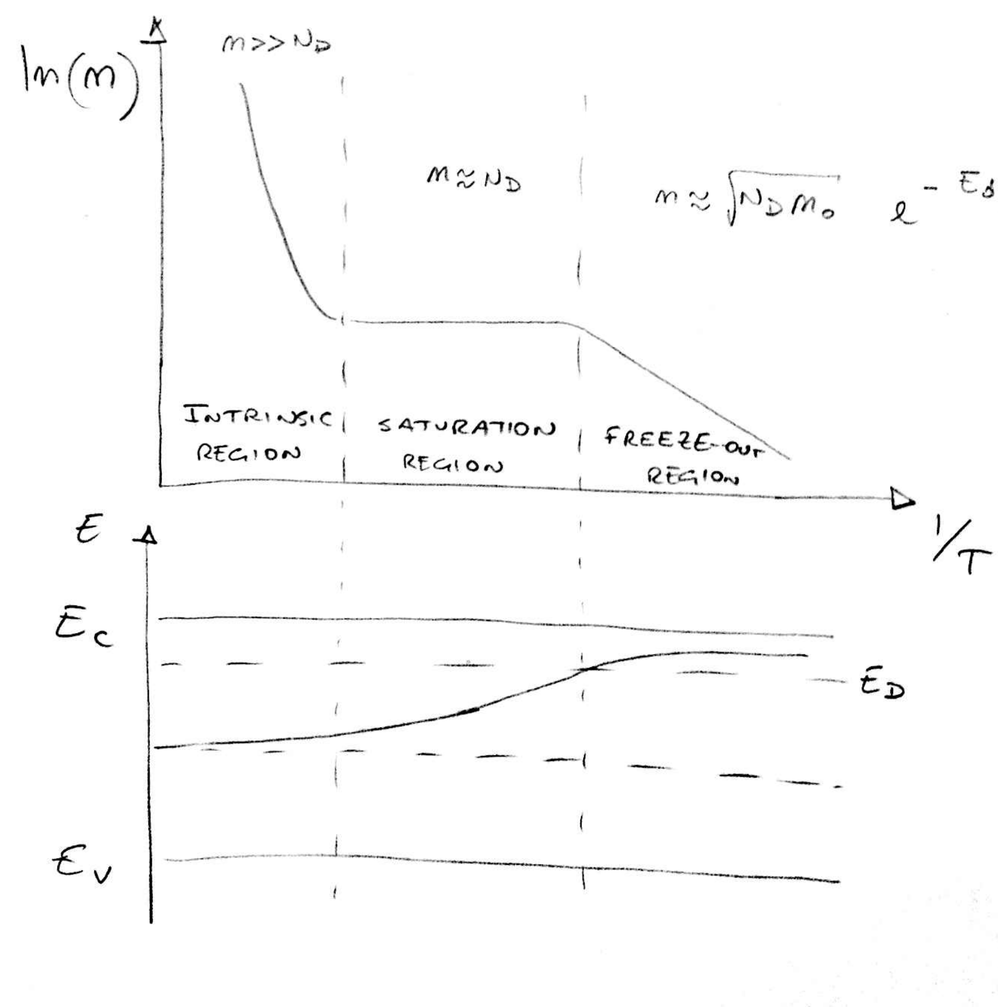
Remember that $\quad k_B T \big|_{T=300K} = 26$ meV

In a doped semiconductor an electron in conduction band can originate either from the valence band or from the ionization of a donor. Similarly the holes in VB





The position of the Fermi level E_F is governed by a rather complicated dependence of temperature, which takes into account the impurities (dopants)

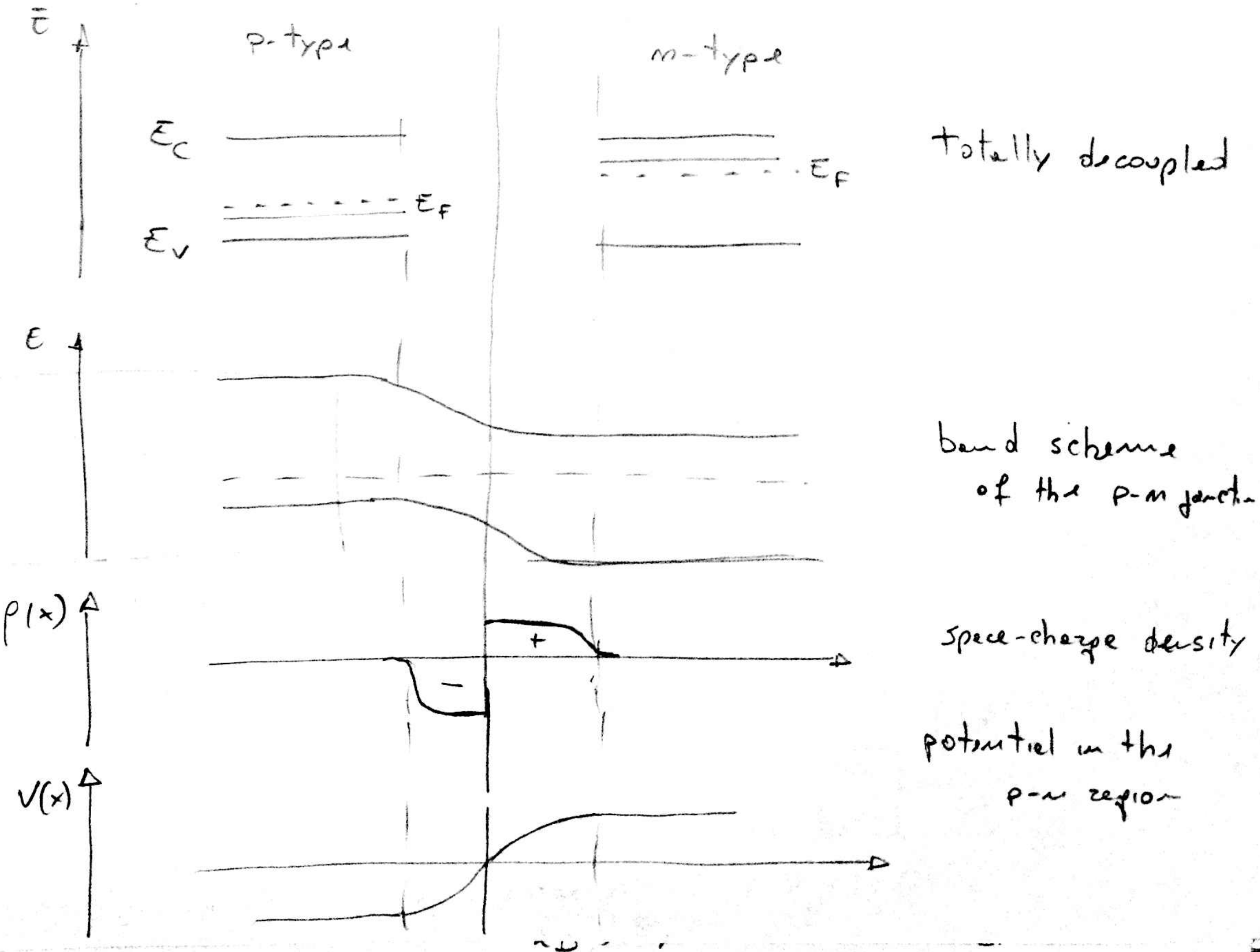


Inhomogeneous Semiconductors: p-n junctions, Metal-Sm schottky contact, Sm-Sm heterojunctions

Modern solid state physics is closely associated with development of semiconductor devices. The operation of almost all semiconductor devices relies on phenomena that are due to heterojunctions or inhomogeneities in doping

– The p-n junction

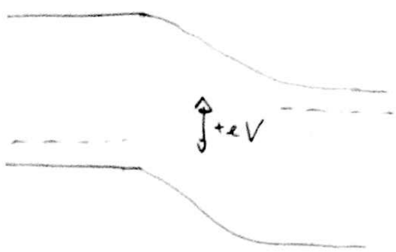
One of the most important building blocks in semiconductor devices is the p-n junction.

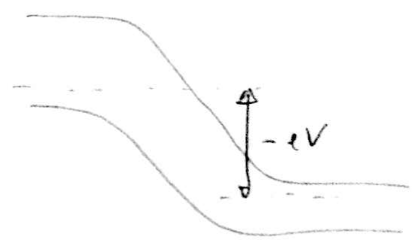


Rectification behavior of the p-n junction

Forward Bias

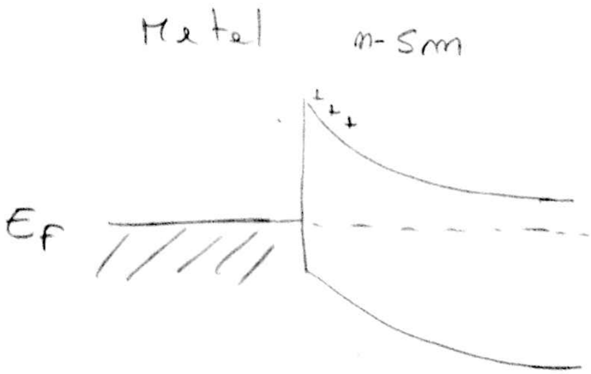
Reverse Bias





An illuminated p-n junction produces a <u>photovoltaic effect</u> (forward voltage). The junction can deliver power to an external circuit. Large p-n in Si are used in solar panels

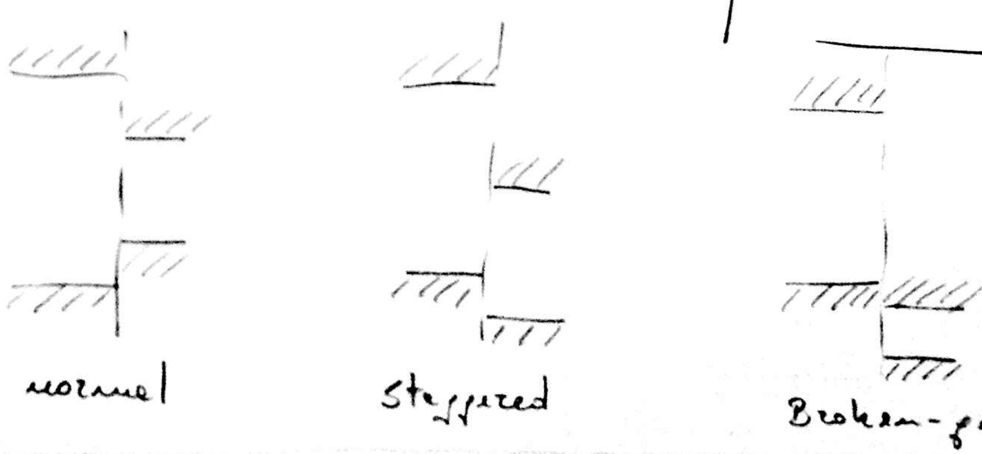
The Metal-Sm Schottky Contact



as for the p-n junction the depletion space-charge region exhibits a resistance

Sm-Sm heterojunctions

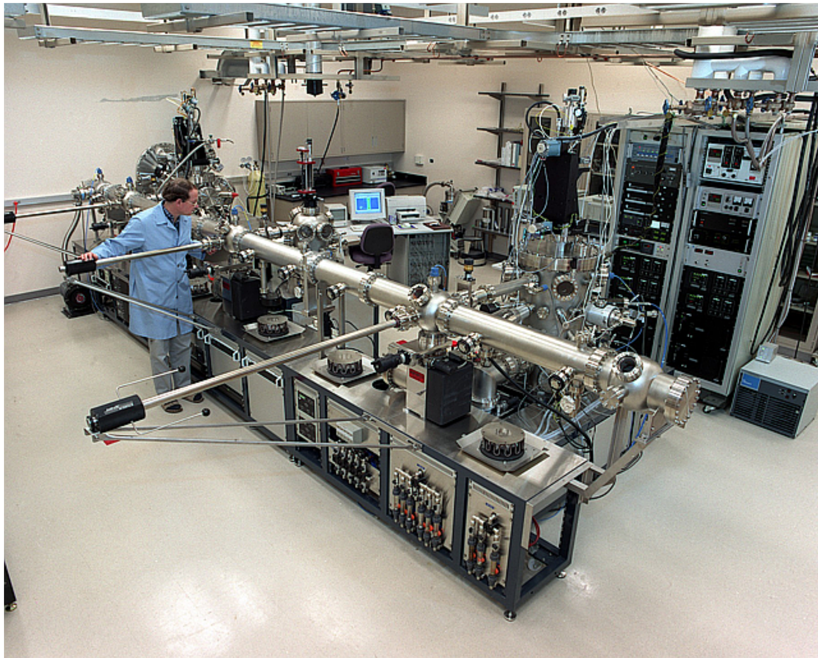
See Power Point presentation

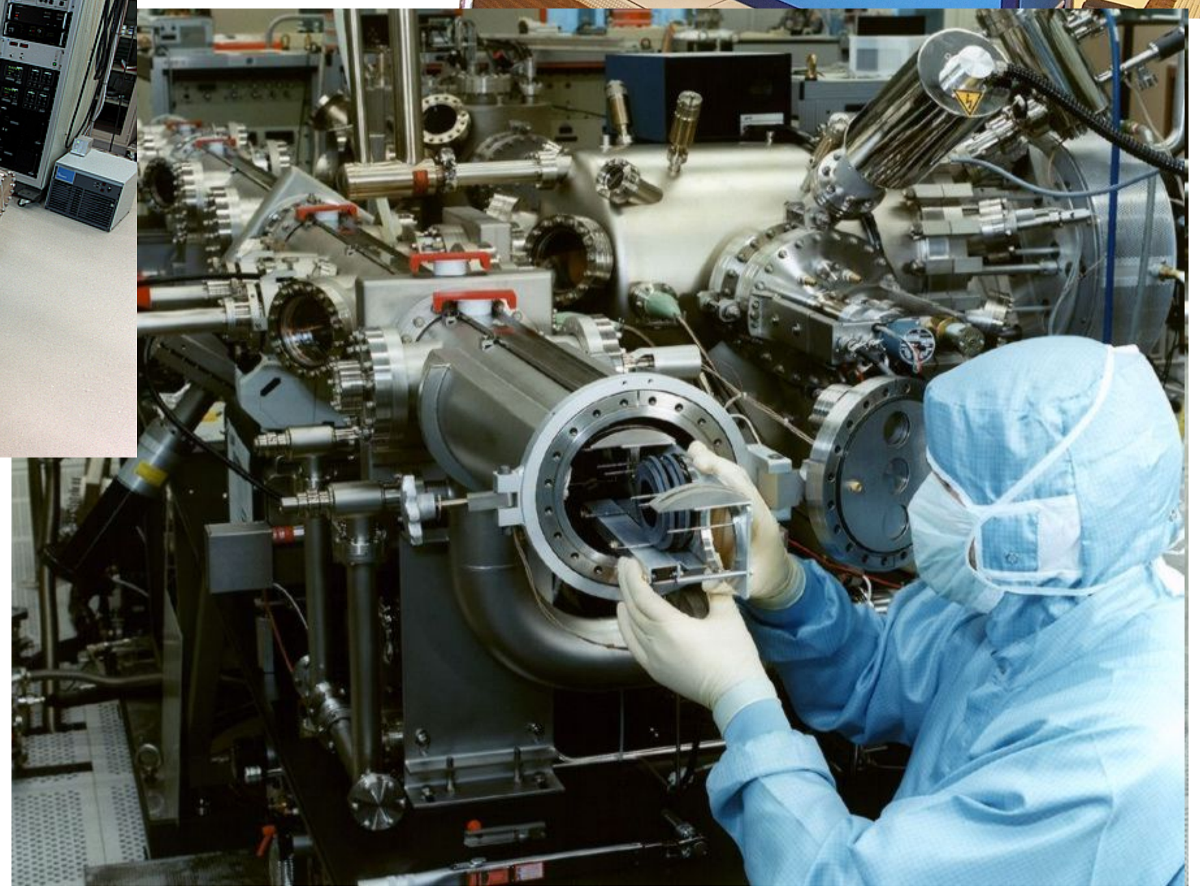


Epitaxial Growth Techniques

MOCVD or MOVPE (Metal-Organic Vapour Phase Epitaxy)

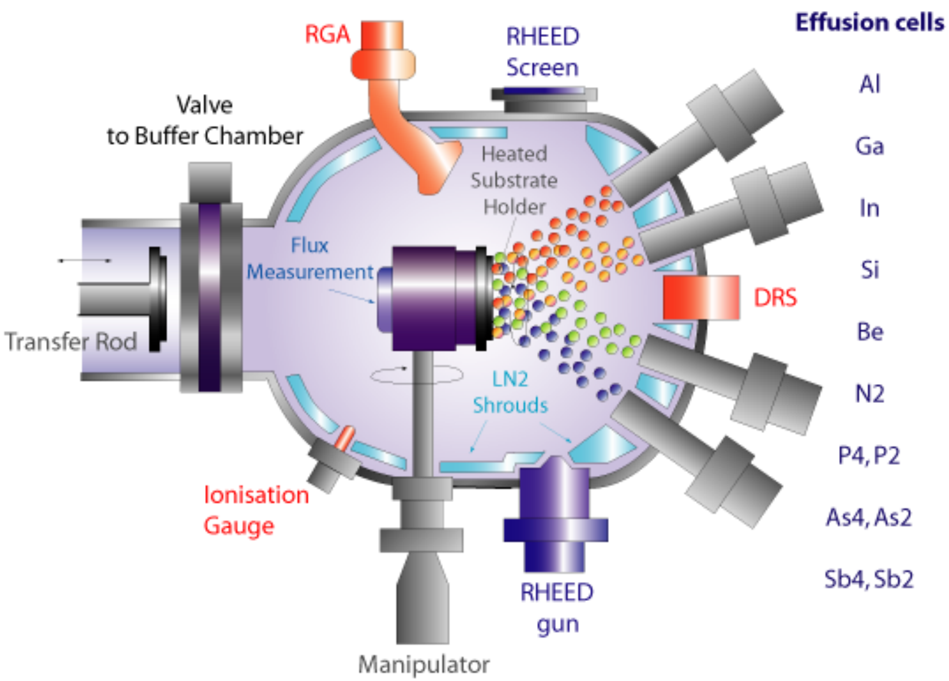
Molecular Beam Epitaxy (MBE)

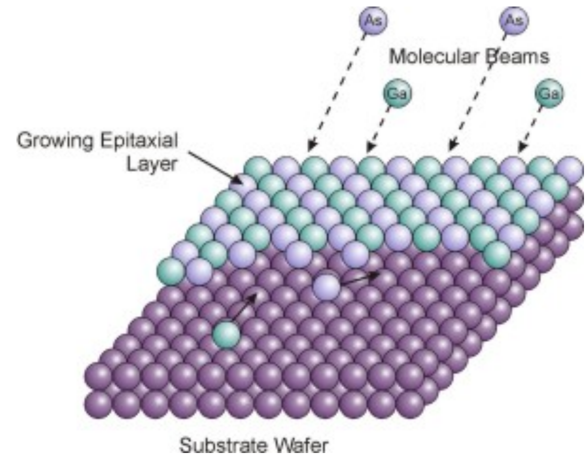


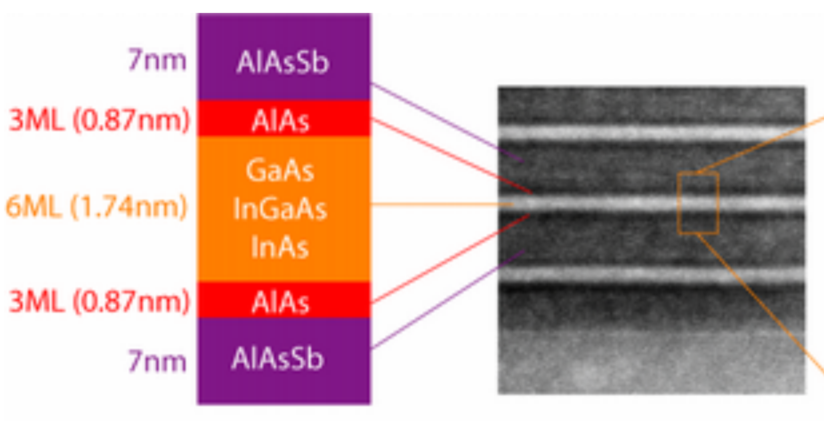


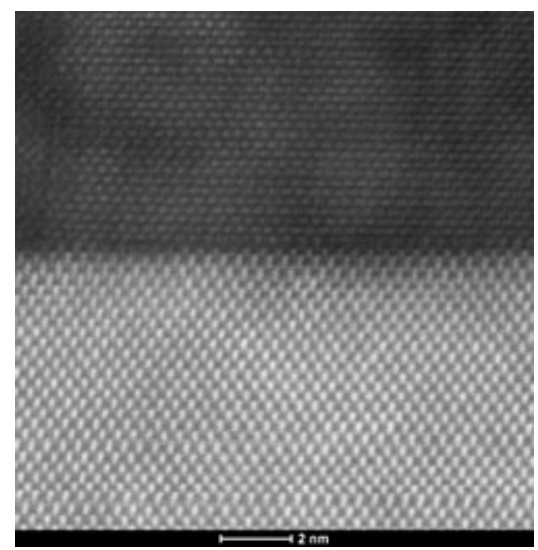
Epitaxial Growth Techniques

Molecular Beam Epitaxy (MBE)









Bandgap Energy vs. Lattice Constant

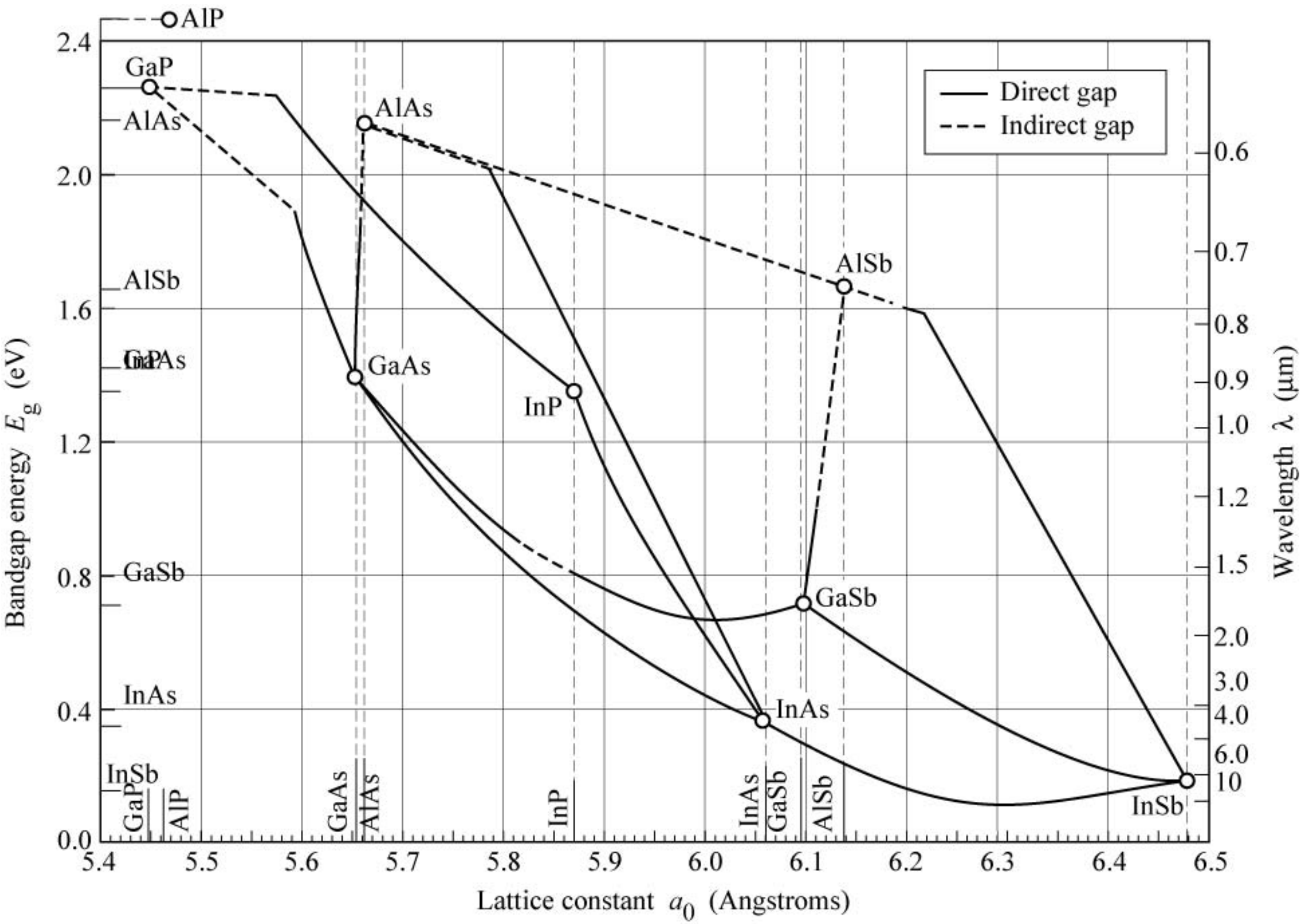
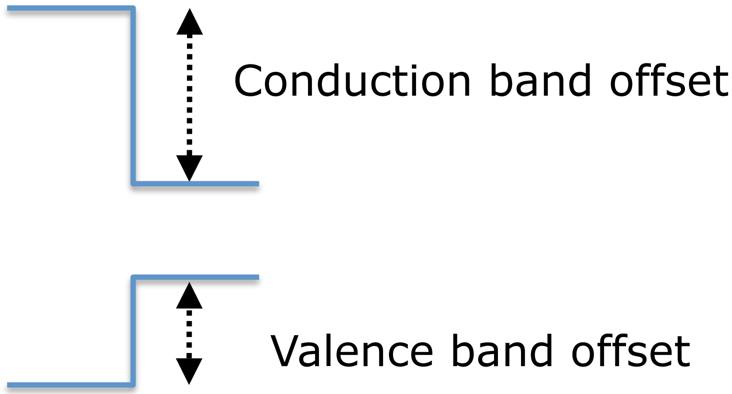


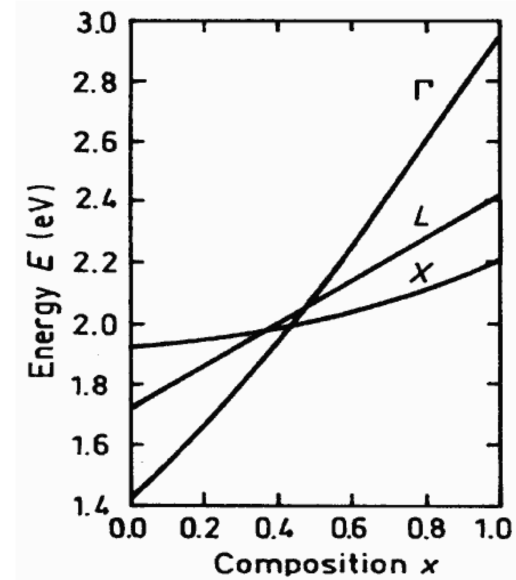
Fig. 12.6. Bandgap energy and lattice constant of various III–V semiconductors at room temperature (adopted from Tien, 1988).

E. F. Schubert

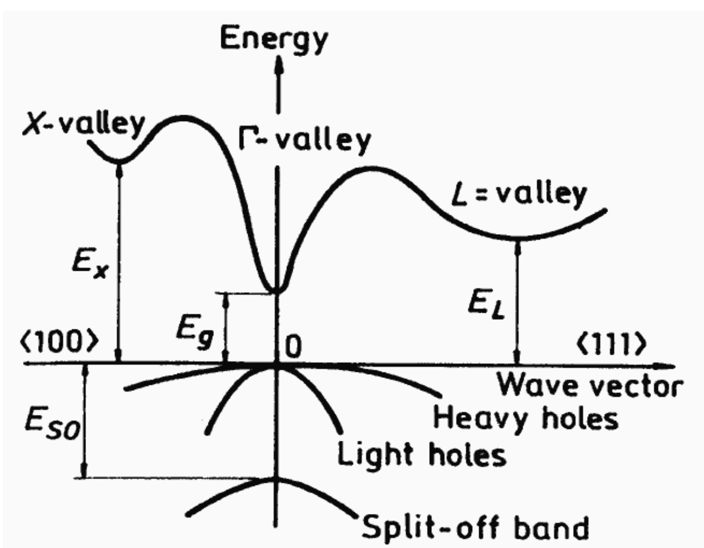
The use of alloy and heterostructures adds a great versatility to the available parameter space.

The $Al_xGa_{1-x}As/GaAs$ Heterojunctions

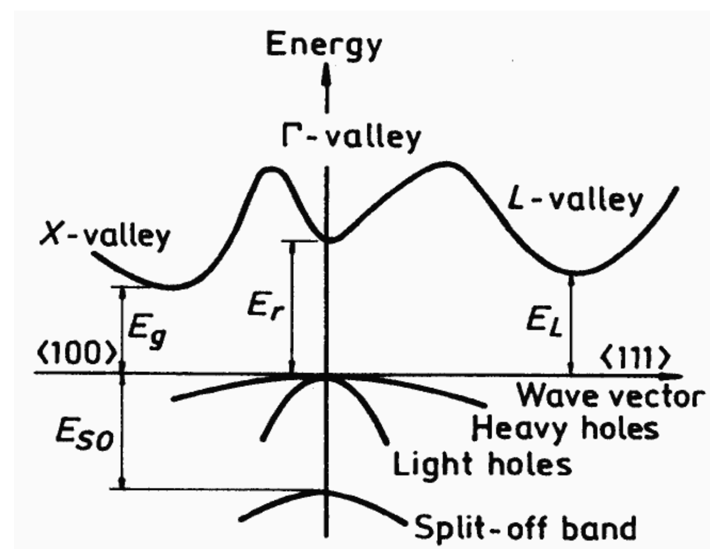




Energy separation between Γ-, X-, and L-conduction band minima and top of the valence band versus composition.



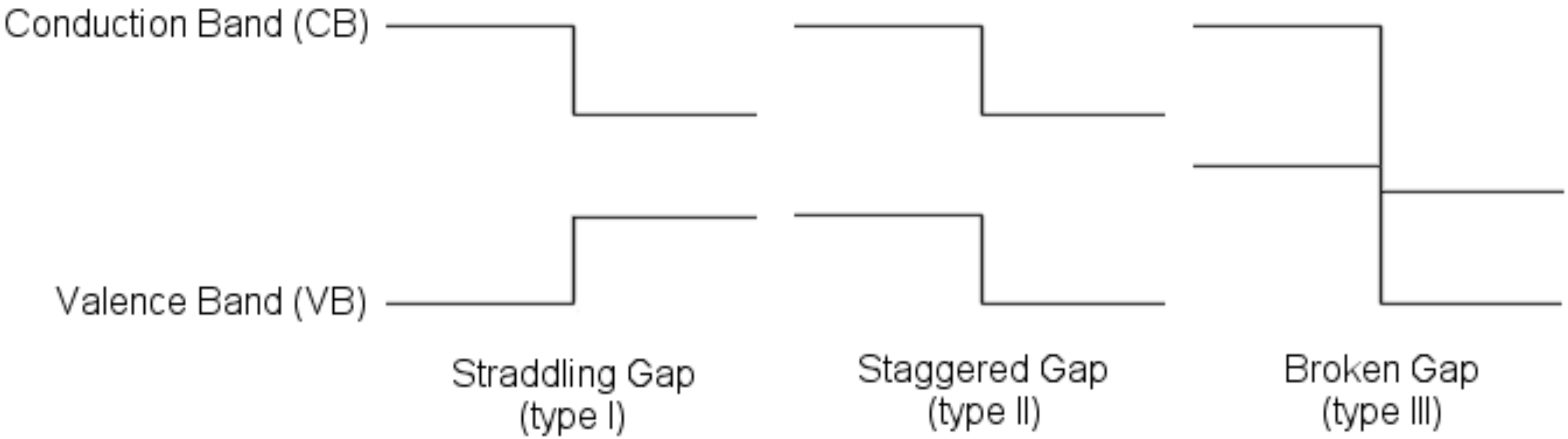
Band structure $Al_xGa_{1-x}As$ for x < 0.41-0.45



Band structure $Al_xGa_{1-x}As$ for x > 0.45

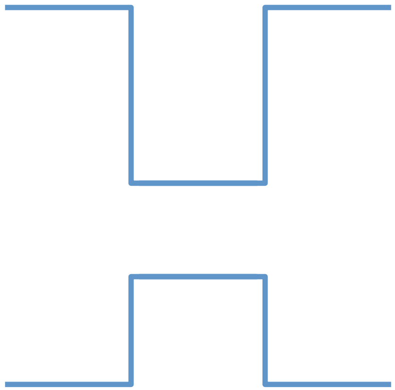
Heterojunctions

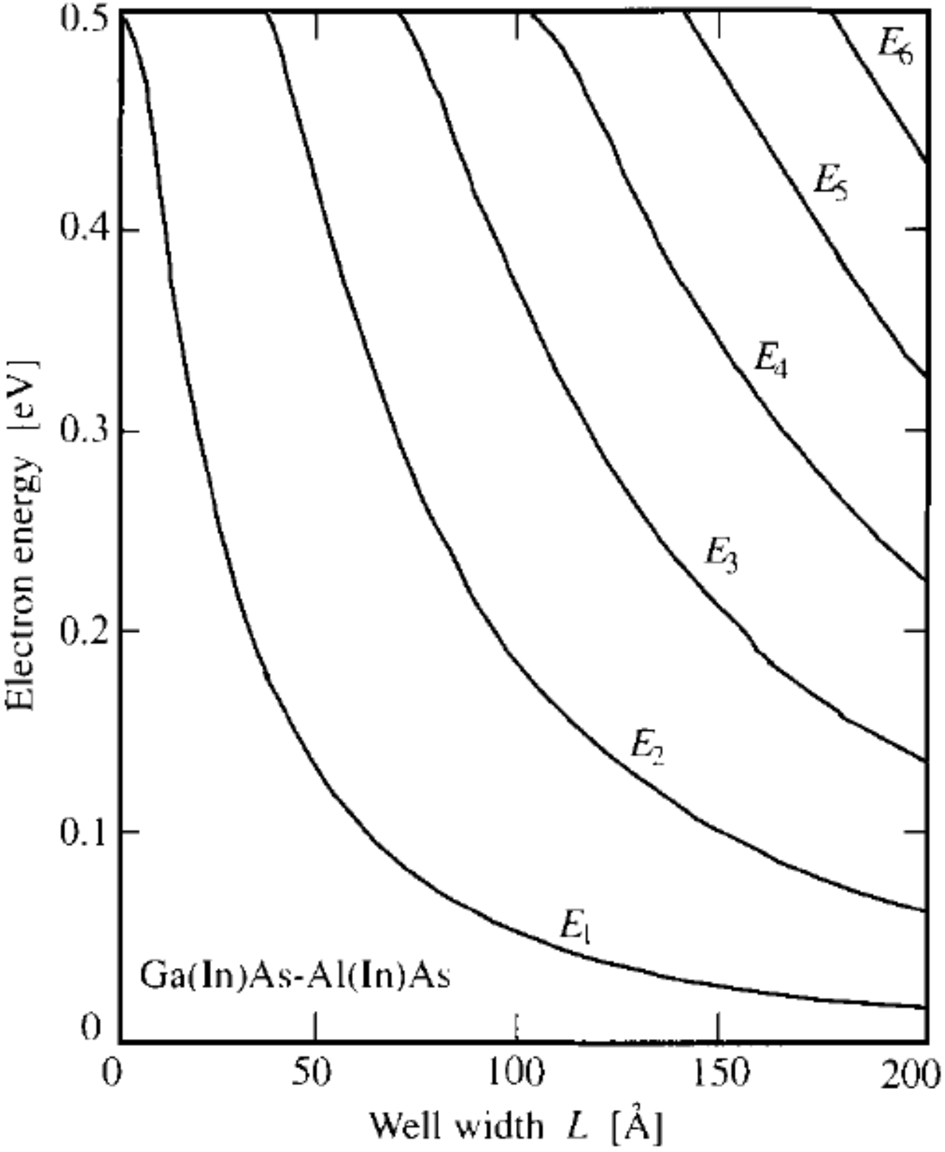
A heterojunction is the interface that occurs between two layers or regions of dissimilar crystalline semiconductors.



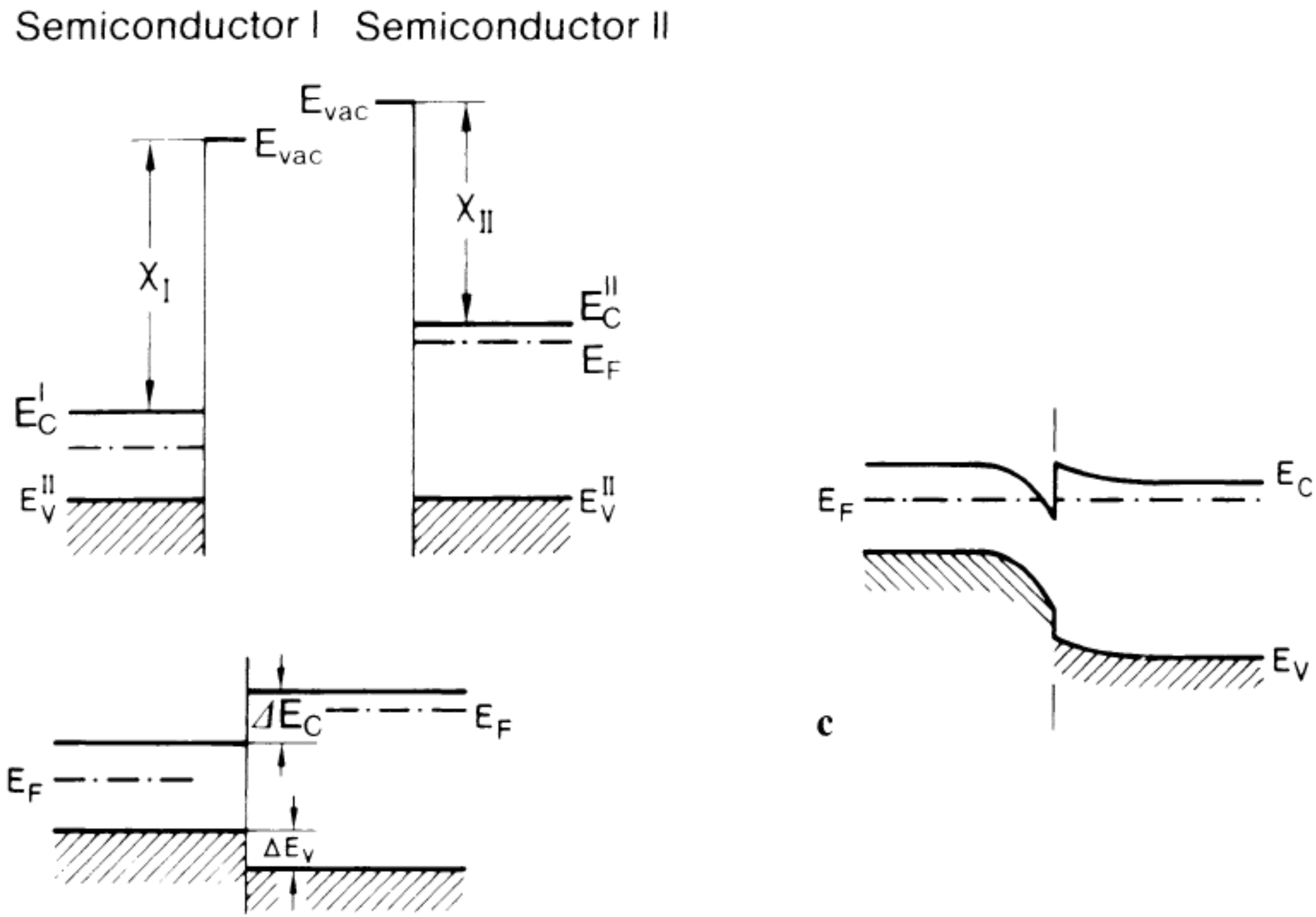
e.g.: $Al_{0.3}Ga_{0.7}As/GaAs$ AlSb/InAs GaSb/InAs

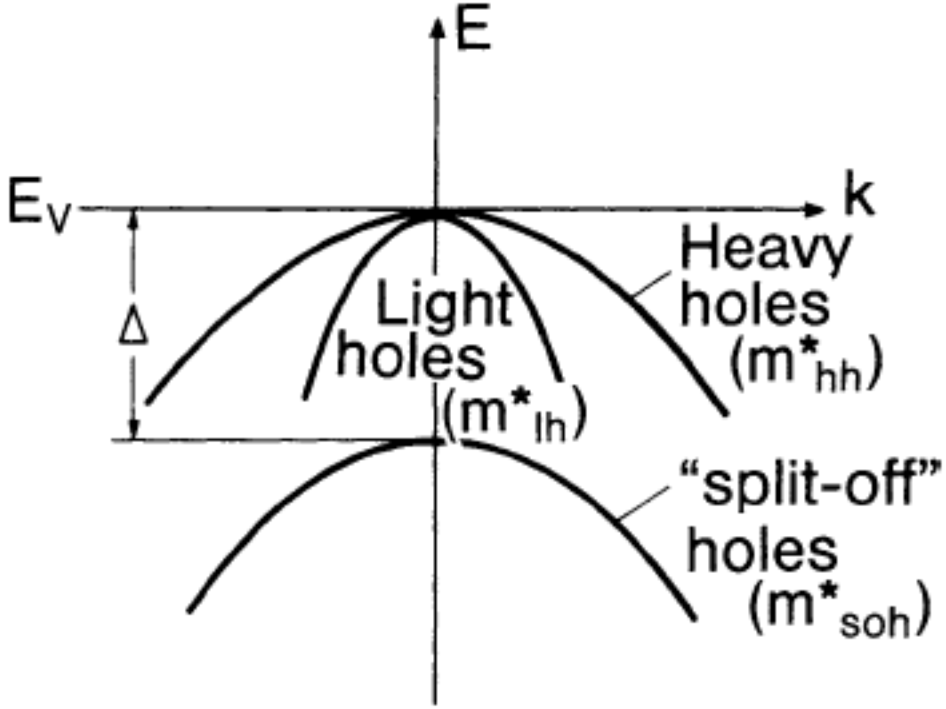
Spatial Confinement of Electrons in Quantum Wells

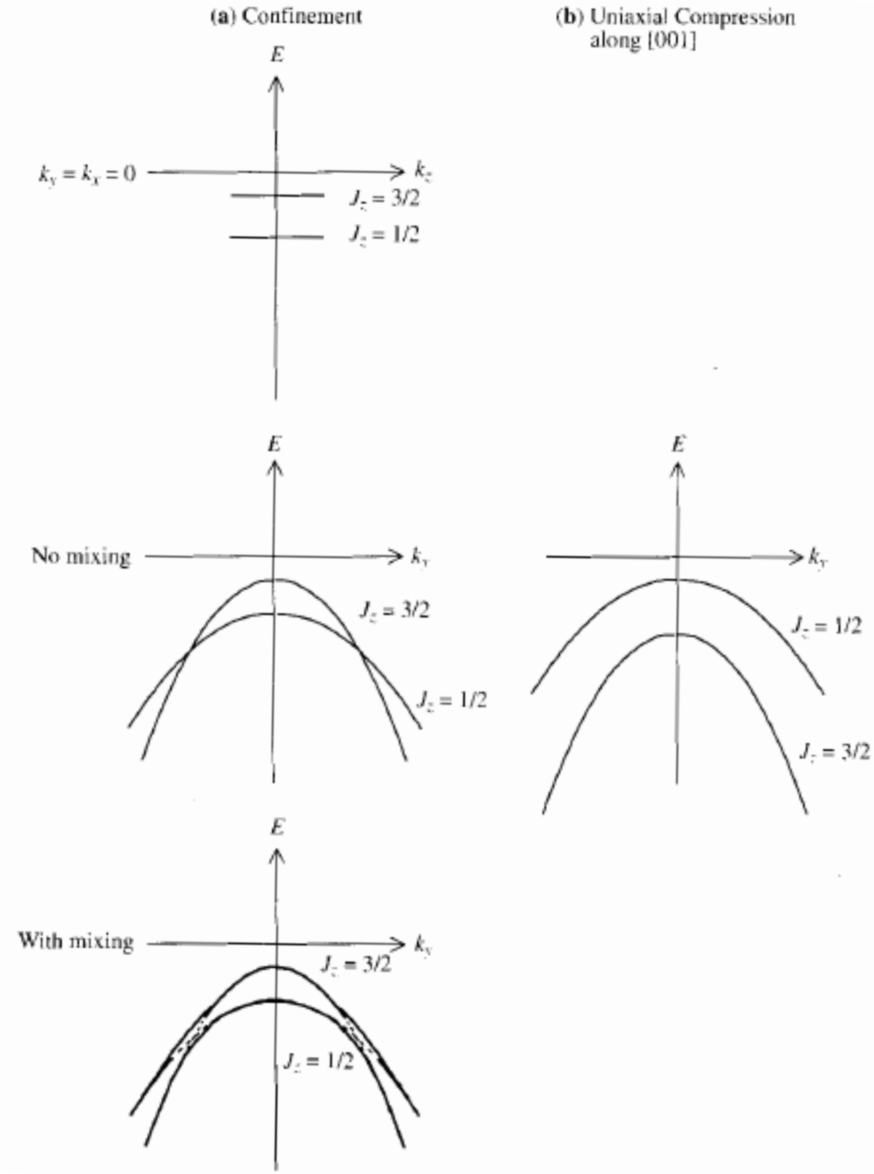


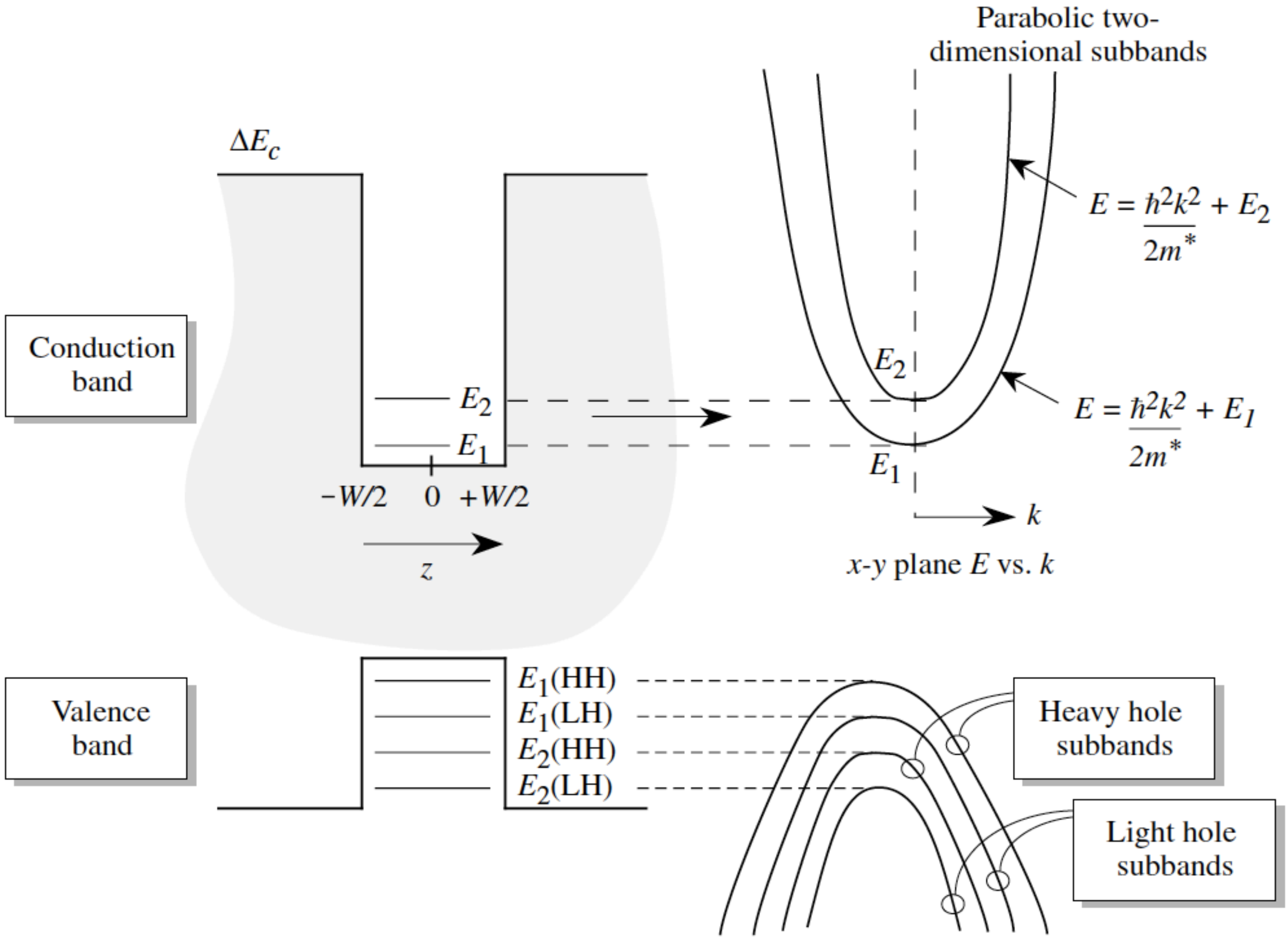


Heterojunctions




E
k
E_V
Δ
Heavy holes (m*hh)
Light holes (m*lh)
"split-off" holes (m*soh)


(a) Confinement
(b) Uniaxial Compression along [001]
E
k_y = k_x = 0
k_z
J_z = 3/2
J_z = 1/2
No mixing
k_y
With mixing



Parabolic two-dimensional subbands
ΔE_c
Conduction band
E_2
E_1
−W/2
0
+W/2
z
E = ħ²k²/2m* + E_2
E = ħ²k²/2m* + E_1
E_2
E_1
k
x-y plane E vs. k
Valence band
E_1(HH)
E_1(LH)
E_2(HH)
E_2(LH)
Heavy hole subbands
Light hole subbands

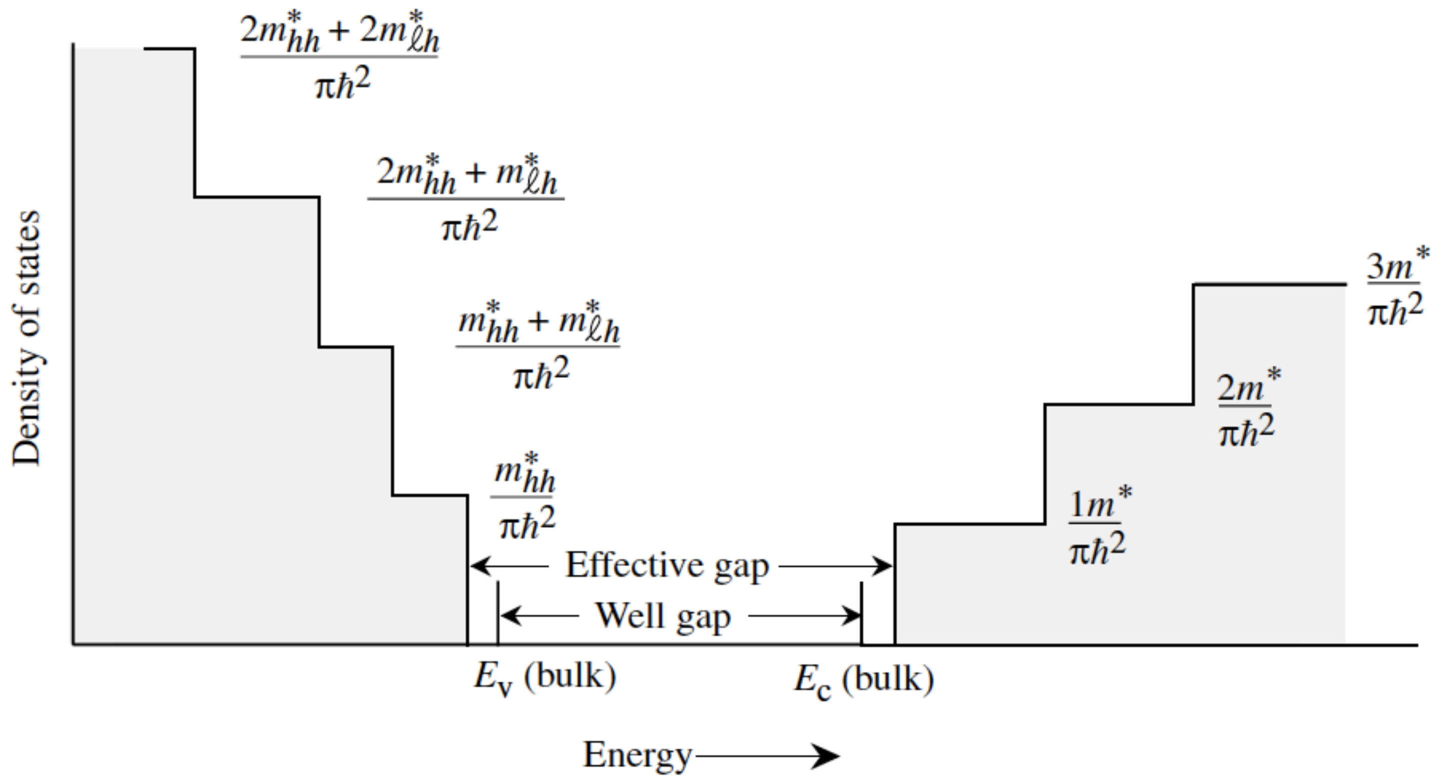
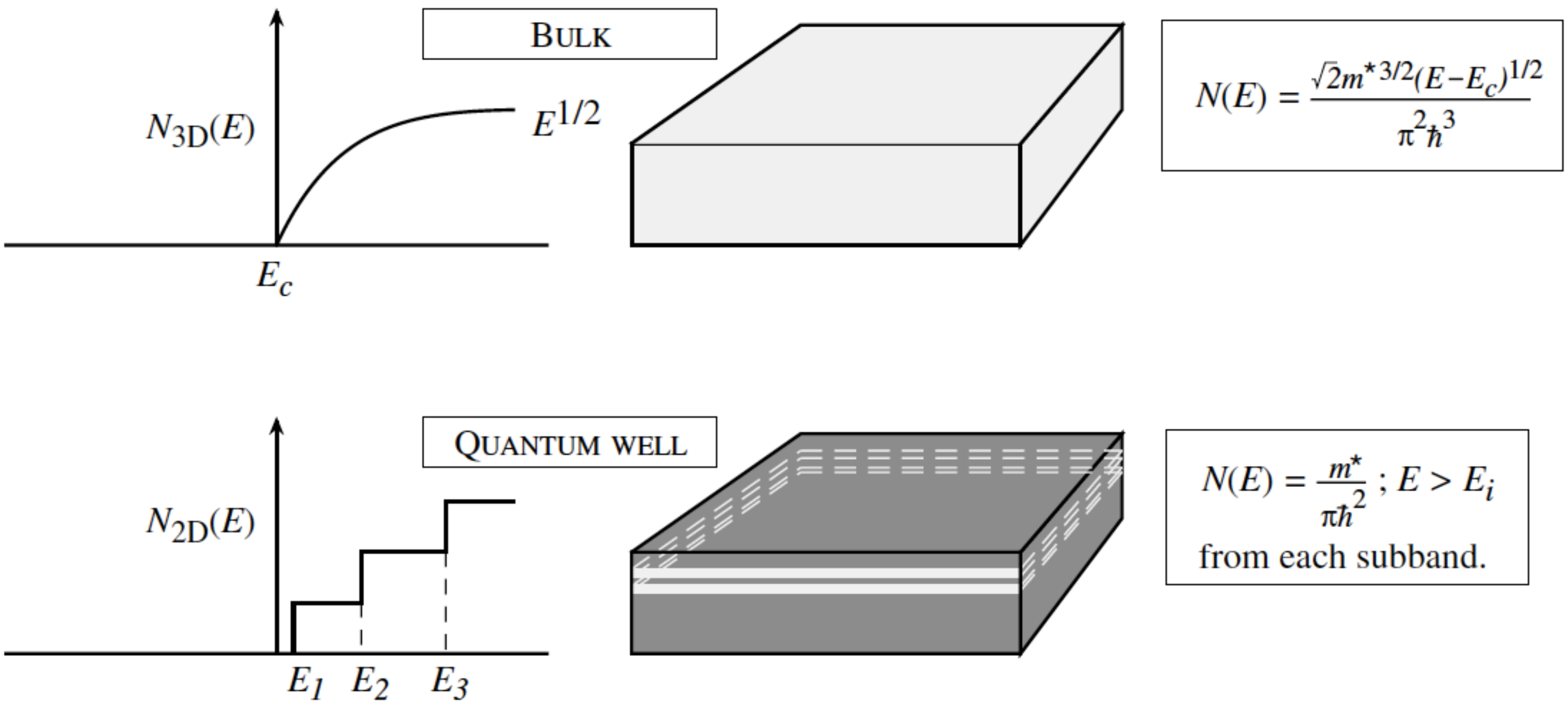


Figure 3.11: Schematic of density of states in a 3–, 2– and 1–dimensional system with parabolic energy momentum relations.


BULK
$N_{3D}(E)$
$E^{1/2}$
E_c
$N(E) = \frac{\sqrt{2}m^{\star 3/2}(E-E_c)^{1/2}}{\pi^2\hbar^3}$
QUANTUM WELL
$N_{2D}(E)$
E_1 E_2 E_3
$N(E) = \frac{m^\star}{\pi\hbar^2}$; $E > E_i$
from each subband.

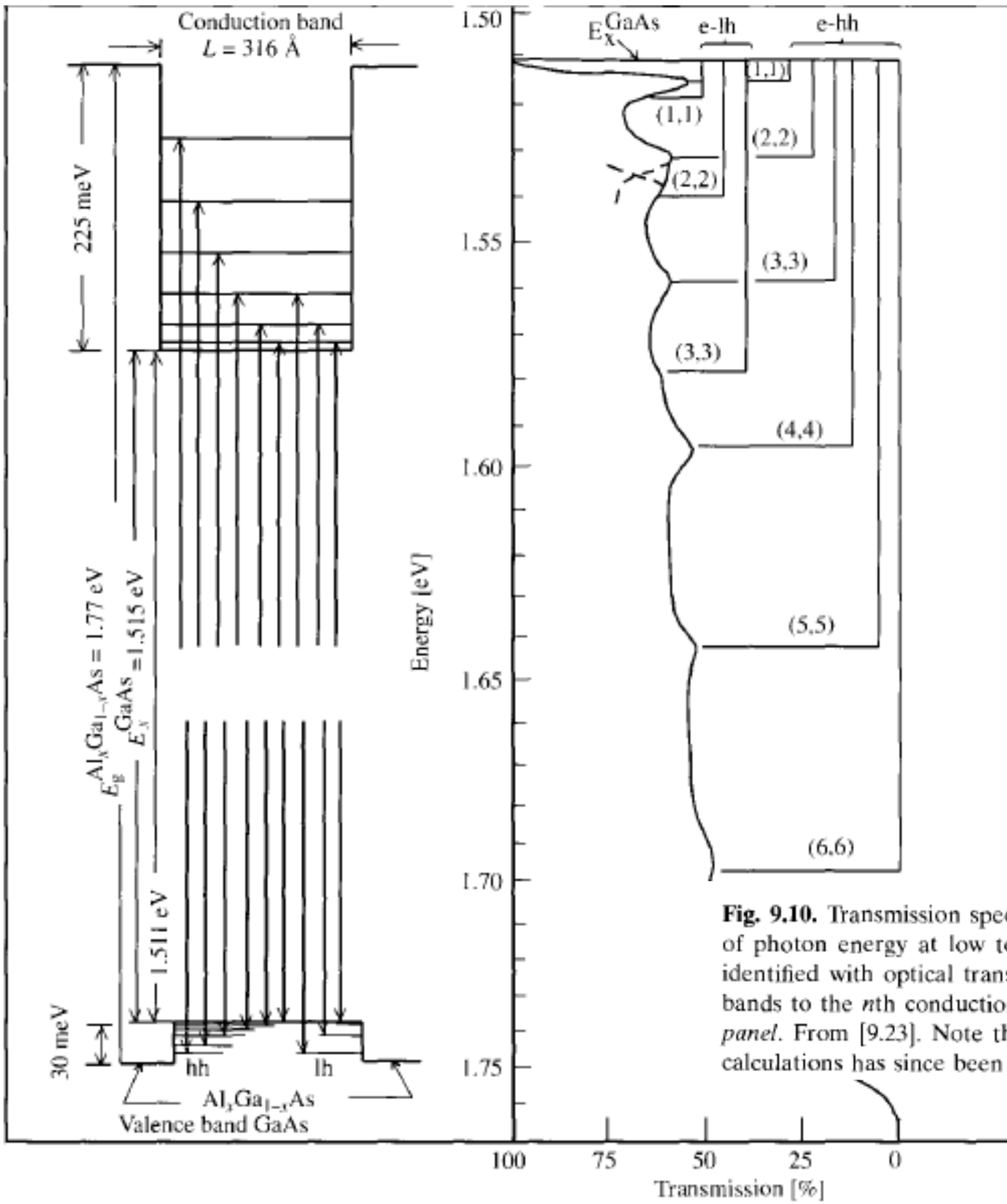
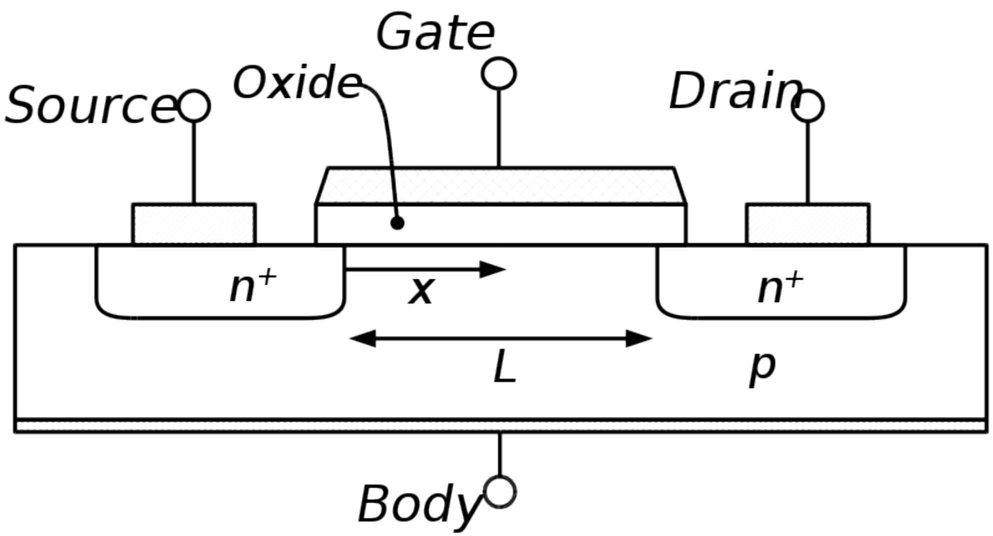
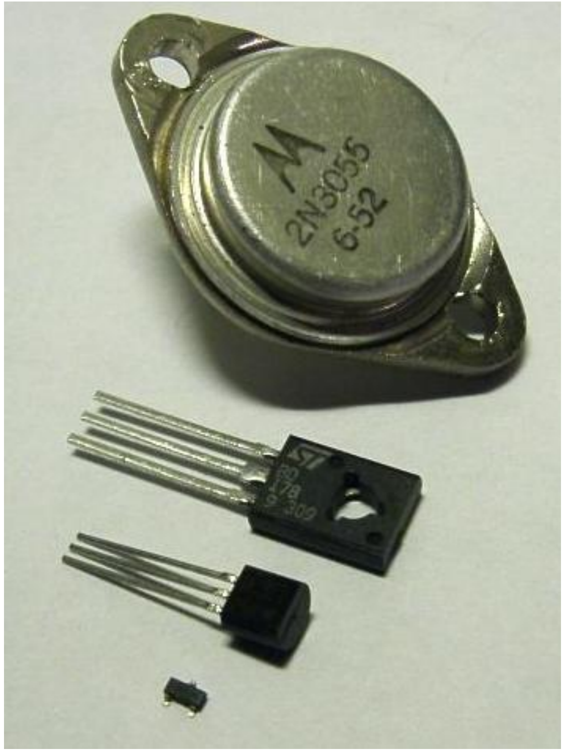


Fig. 9.10. Transmission spectrum of 316 Å GaAs/AlGaAs MQW measured as a function of photon energy at low temperature (*right panel*). The peaks labeled (n,n) have been identified with optical transitions from the nth heavy hole (hh) and light hole (1h) subbands to the nth conduction subband as shown by *arrows* in the band diagram in the *left panel*. From [9.23]. Note that the value of the band offset assumed by Dingle for these calculations has since been revised

Field-effect Transistor

The field-effect transistor (FET) is a transistor that relies on an electric field to control the shape and hence the conductivity of a channel of one type of charge carrier in a semiconductor material





Field-effect Transistor

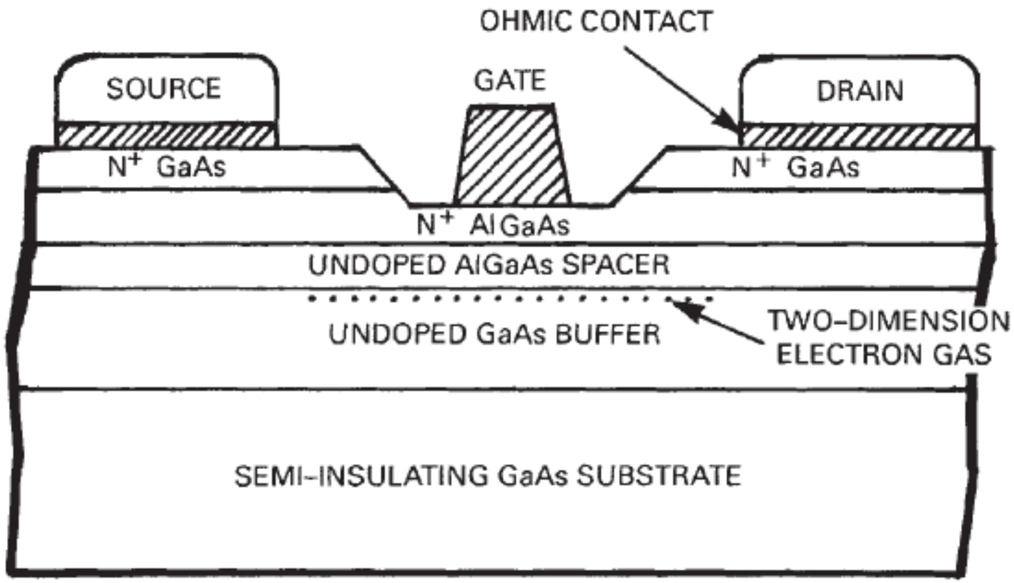
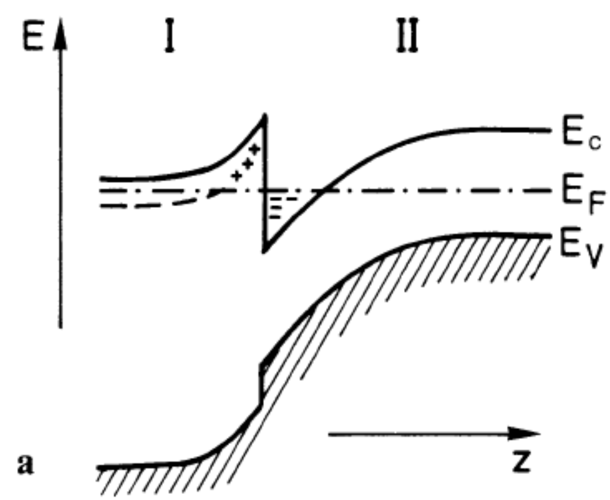
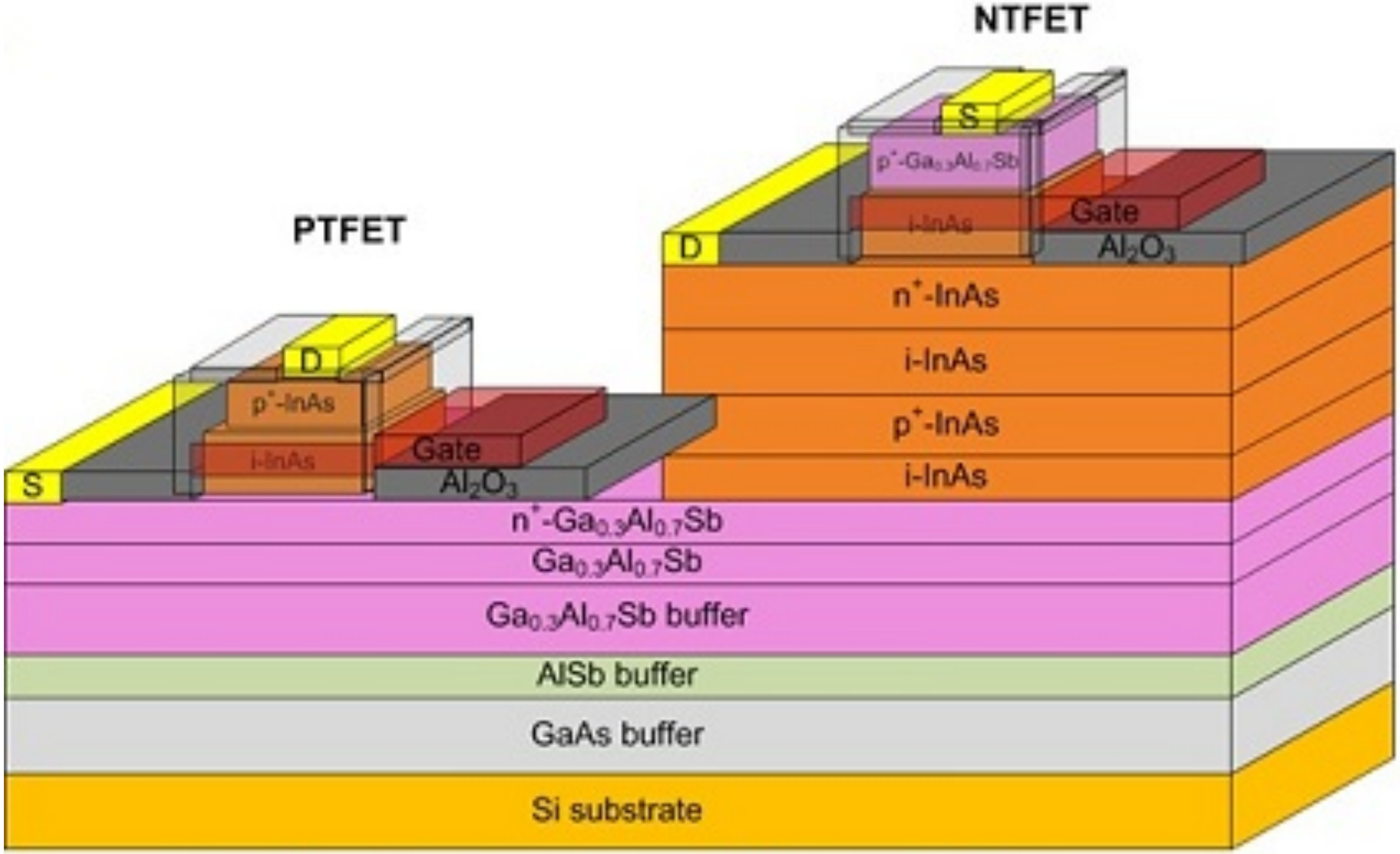


Figure 2-13 High-electron-mobility transistor (HEMT).



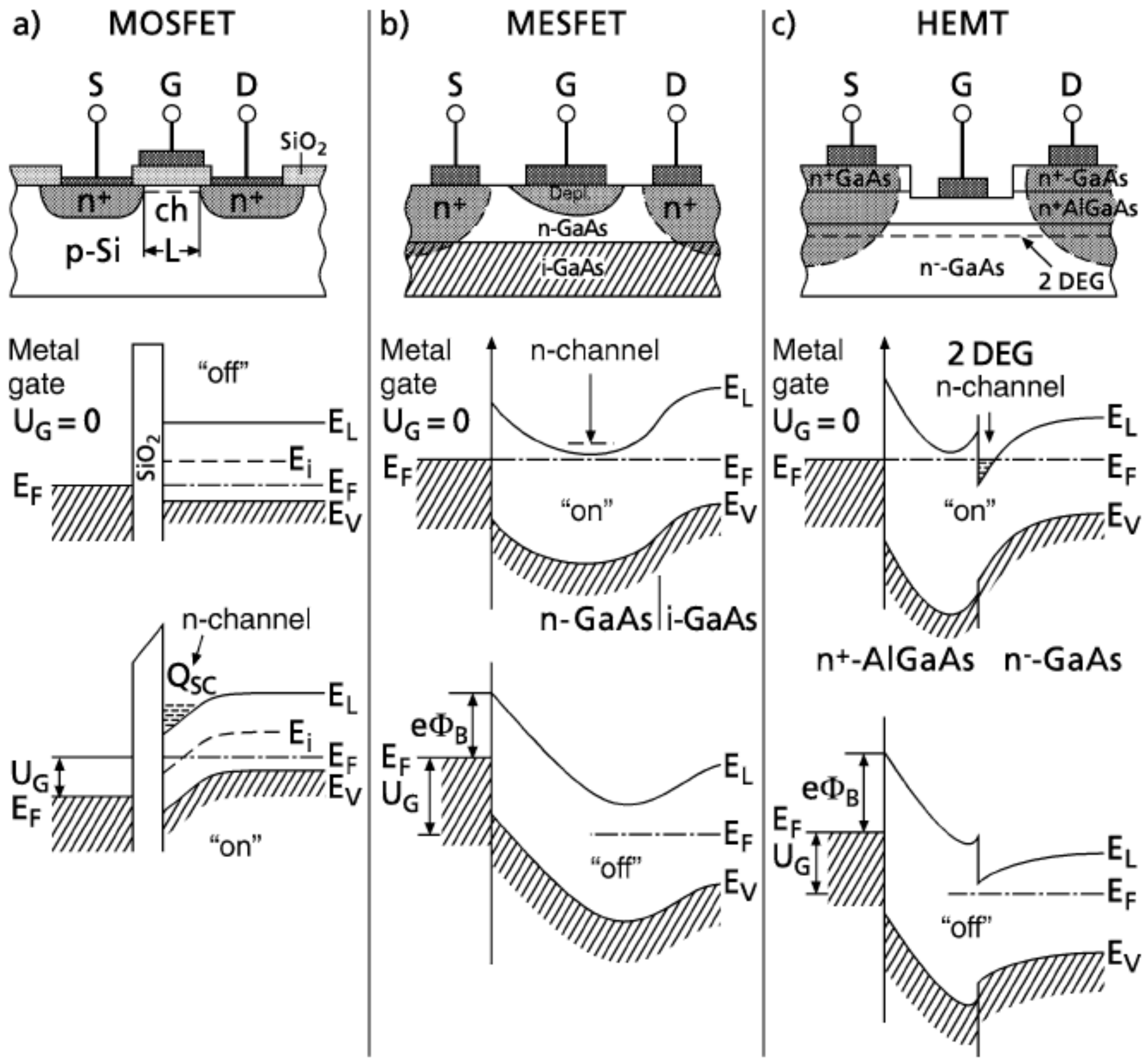
Field-effect Transistor



Complimentary Tunnel FET structure

Field-effect Transistor

High Electron Mobility



Semiconductor Lasers

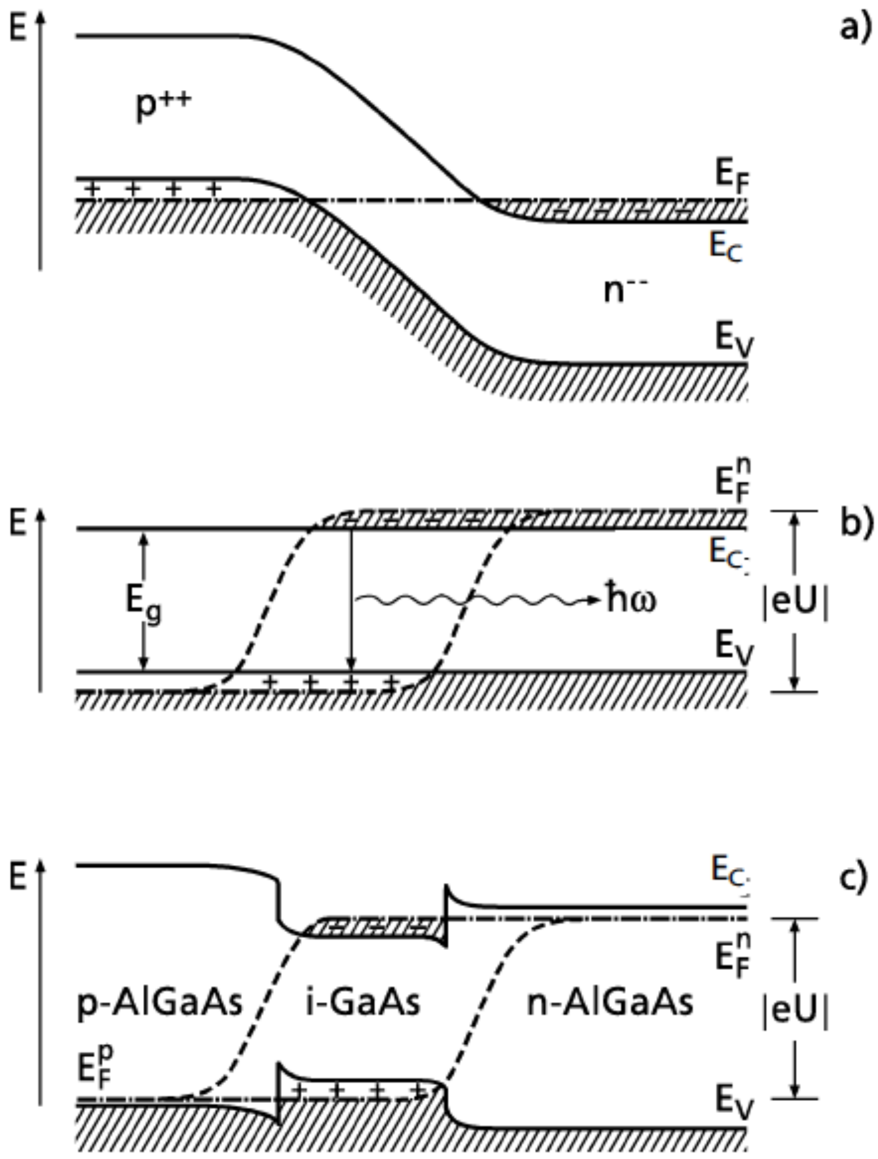


Fig. 12.37. Electronic band schemes $E(x)$ of *pn*-semiconductor laser structures along a direction x perpendicular to the layer structure: (**a**) Degenerately doped $p^{++}n^{--}$ junction without external bias (thermal equilibrium); (**b**) same $p^{++}n^{--}$ junction with maximum bias U in forward direction; (**c**) double-heterostructure pin junction of *p*-AlGaAs/*i*-GaAs/*n*-AlGaAs with maximum bias U in forward direction. E_F^n, E_F^p are the quasi-Fermi levels in the *n*- and *p*-region, respectively; E_C and E_V are conduction and valence band edges

Semiconductor Lasers

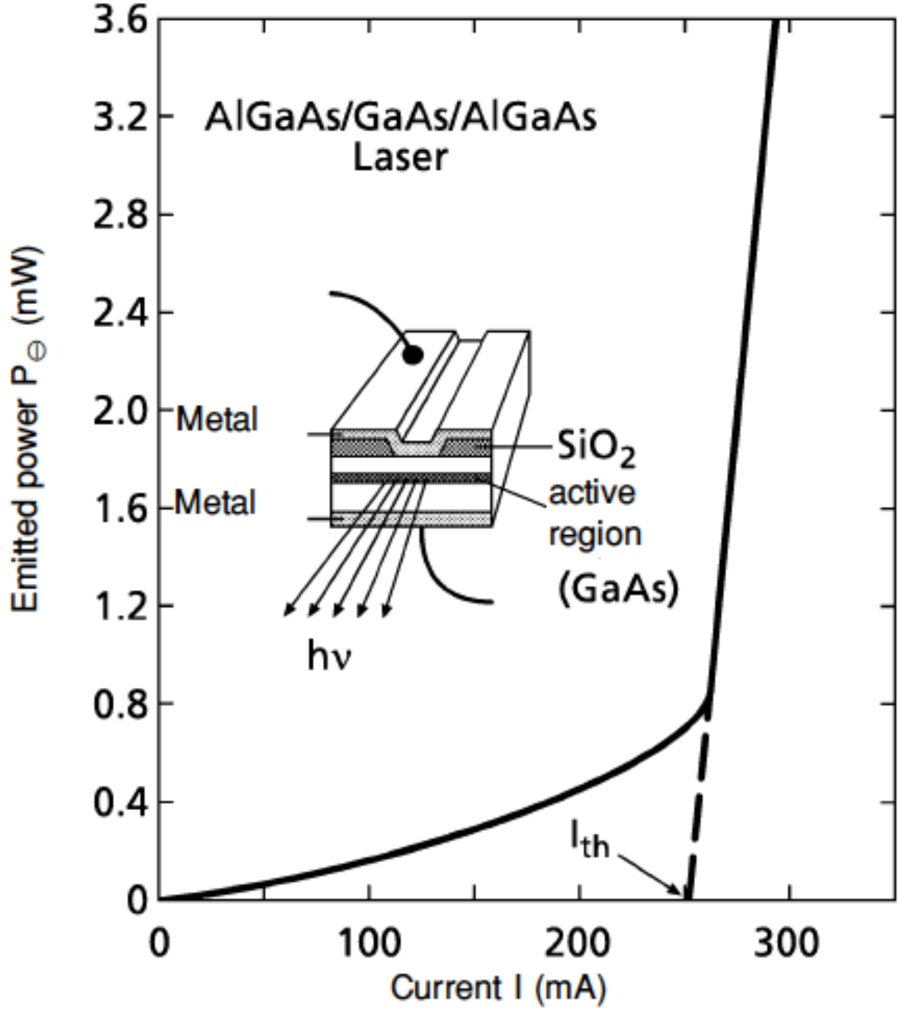


Fig. 12.38. Emission characteristics at room temperature $T = 300$ K of an AlGaAs/GaAs/AlGaAs double-heterostructure laser: the emitted light power is plotted as a function of the current I through the laser; I_{th} is the threshold current where laser action begins. Inset: Schematic layer structure of the laser with emitted radiation ($h\nu$). (After Kressel and Ackley [12.16])

Semiconductor Lasers