3.15
Carrier Fundamentals
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Reference: Pierret, chapters 1-2.

Electron and hole charge: $e = 1.6\ 10^{-19}$ C
Effective mass: m^*, rest mass m_o

$F = -eE = m_o\ dv/dt$ in vacuum
$F = -eE = m^*\ dv/dt$ in solid

in Si, $m_n^*/m_o = 1.18$, $m_h^*/m_o = 0.81$ at 300K.

<u>Intrinsic properties</u>

in Si, $n = p = 10^{10}\ cm^{-3}$ at 300K
$N = 5\ 10^{22}$ atoms cm^{-3}

<u>Extrinsic properties</u>

Donors – group V
Acceptors – group III

B	C	N	O	
Al	Si	P	S	
Ga	Ge	As	Se	
In	Sn	Sb	Te	
Tl	Pb	Bi	Po	

Band diagrams: E_c = conduction band edge, E_v = valence band edge

band gaps:		
	Si	1.12 eV
	diamond	5.4 eV
	silica	5 eV

energies of dopant levels, in meV, in silicon (kT = 26 meV @ 300K)

P	45	B	45
As	54	Al	67
		Ga	72

Carrier distributions (intrinsic)

$g(E)\,dE$ = density of electron states cm^{-3} in the interval $(E, E+dE)$, units $\#/eV.cm^{-3}$

$$g_c(E)\,dE = m_n^*\sqrt{2m_n^*(E - E_c)} / (\pi^2 \hbar^3)\,dE$$
$$g_v(E)\,dE = m_p^*\sqrt{2m_p^*(E_v - E)} / (\pi^2 \hbar^3)\,dE$$

In these states, the electrons distribute according to Fermi function

$$f(E) = 1/\{1 + \exp(E - E_f)/kT\}$$

Number of electrons in the interval $(E, E+dE)$ is therefore $f(E)g(E)dE$.
In a doped semiconductor, the position of E_f with respect to the band gap determines whether there are more electrons or holes.

Total number of electrons: by integrating $f(E)g(E)dE$

$$n = n_i \exp(E_f - E_i)/kT$$
$$p = n_i \exp(E_i - E_f)/kT$$

where

$$n_i = N_c \exp(E_i - E_c)/kT$$
$$N_c = 2\{2\pi m_n^* kT/h^2\}^{3/2} = \text{'effective density of conduction band states'}$$

E_i is the position of the Fermi level in the intrinsic case.
Similarly for N_v.

Hence

$$np = n_i^2 \text{ at equilibrium}$$
$$n_i^2 = N_c N_v \exp(E_v - E_c)/kT = N_c N_v \exp(-E_g)/kT$$

Intrinsic case:

$$E_i = (E_v + E_c)/2 + 3/4\, kT \ln(m_p^*/m_n^*)$$

In a doped material, where $n \sim N_D$ or $p \sim N_A$

$$E_f - E_i = kT \ln(n/n_i) = -kT \ln(p/n_i)$$
$$\sim kT \ln(N_D/n_i) \quad \text{or} \quad -kT \ln(N_A/n_i)$$

n-type p-type

Properties	Si	GaAs	SiO_2	Ge
Atoms/cm^3, molecules/cm^3 x 10^{22}	5.0	4.42	2.27[a]	
Structure	diamond	zincblende	amorphous	
Lattice constant (nm)	0.543	0.565		
Density (g/cm^3)	2.33	5.32	2.27[a]	
Relative dielectric constant, ε_r	11.9	13.1	3.9	
Permittivity, $\varepsilon = \varepsilon_r \varepsilon_o$ (farad/cm) x 10^{-12}	1.05	1.16	0.34	
Expansion coefficient (dL/LdT) x (10^{-6} K)	2.6	6.86	0.5	
Specific Heat (joule/g K)	0.7	0.35	1.0	
Thermal conductivity (watt/cm K)	1.48	0.46	0.014	
Thermal diffusivity (cm^2/sec)	0.9	0.44	0.006	
Energy Gap (eV)	1.12	1.424	~9	0.67
Drift mobility (cm^2/volt-sec)				
Electrons	1500	8500		
Holes	450	400		
Effective density of states				
(cm^{-3}) x 10^{19}				
Conduction band	2.8	0.047		
Valence band	1.04	0.7		
Intrinsic carrier concentration (cm^{-3})	1.45 x 10^{10}	1.79 x 10^6		

Properties of Si, GaAs, SiO_2, and Ge at 300 K

Mayer and Lau, Electronic Materials Science

Figure by MIT OCW.

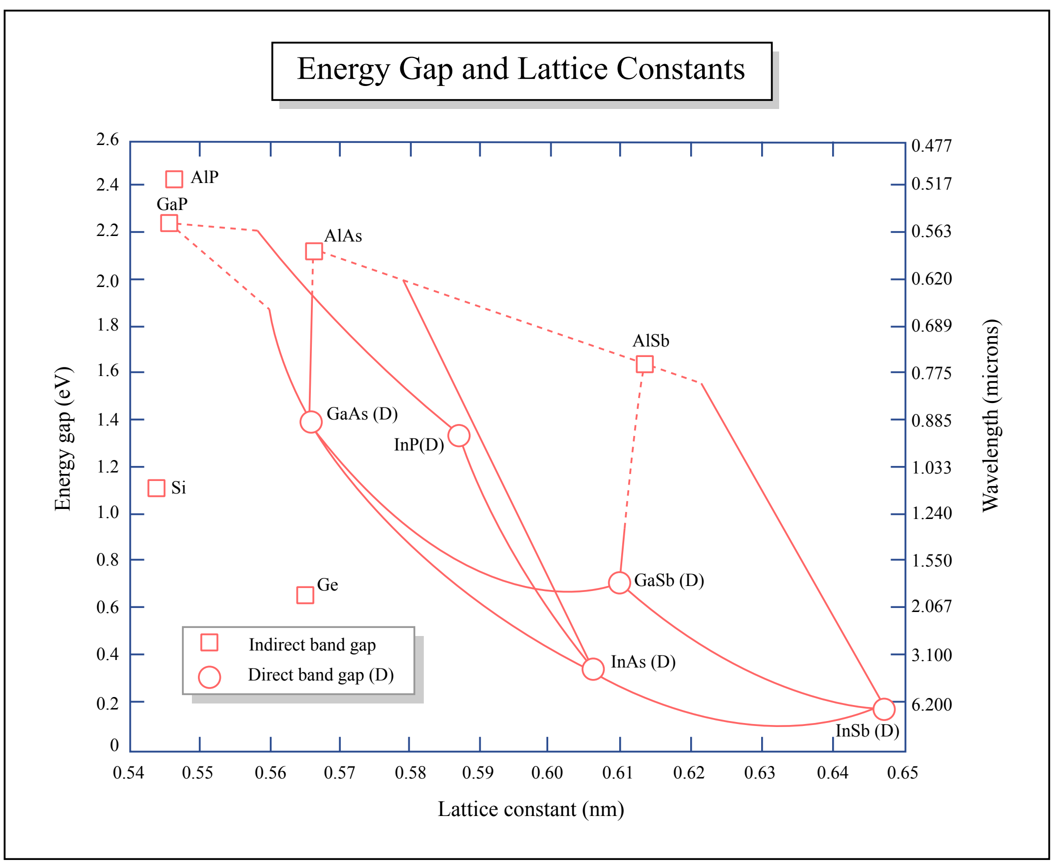

Figure by MIT OCW.

PHYSICAL CONSTANTS, CONVERSIONS, AND USEFUL COMBINATIONS

Physical Constants

Avogadro constant	$N_A = 6.022 \times 10^{23}$ particles/mole
Boltzmann constant	$k = 8.617 \times 10^{-5}$ eV/K $= 1.38 \times 10^{-23}$ J/K
Elementary charge	$e = 1.602 \times 10^{-19}$ coulomb
Planck constant	$h = 4.136 \times 10^{-15}$ eV ·s
	$= 6.626 \times 10^{-34}$ joule ·s
Speed of light	$c = 2.998 \times 10^{10}$ cm/s
Permittivity (free space)	$\varepsilon_0 = 8.85 \times 10^{-14}$ farad/cm
Electron mass	$m = 9.1095 \times 10^{-31}$ kg
Coulomb constant	$k_c = 8.988 \times 10^{9}$ newton-m^2/(coulomb)^2
Atomic mass unit	$u = 1.6606 \times 10^{-27}$ kg

Useful Combinations

Thermal energy (300 K)	$kT = 0.0258$ eV $\simeq$ 1 eV/40
Photon energy	$E = 1.24$ eV at $\lambda =$ µm
Coulomb constant	$k_c e^2$ 1.44 eV · nm
Permittivity (Si)	$\varepsilon = \varepsilon_r \varepsilon_0 = 1.05 \times 10^{-12}$ farad/cm
Permittivity (free space)	$\varepsilon_0 = 55.3e$/V · µm

Prefixes

k = kilo = 10^3; M = mega = 10^6; G = giga = 10^9; T = tera = 10^{12}
m = milli = 10^{-3}; µ = micro = 10^{-6}; n = nano = 10^{-9}; p = pica = 10^{-12}

Symbols for Units

Ampere (A), Coulomb (C), Farad (F), Gram (g), Joule (J), Kelvin (K)

Meter (m), Newton (N), Ohm (Ω), Second (s), Siemen (S), Tesla (T)

Volt (V), Watt (W), Weber (Wb)

Conversions

1 nm = 10^{-9} m = 10 Å = 10^{-7} cm; 1 eV = 1.602×10^{-9} Joule = 1.602×10^{-12} erg;
1 eV/particle = 23.06 kcal/mol; 1 newton = 0.102 kg$_{force}$;
10^6 newton/m^2 = 146 psi = 10^7 dyn/cm^2 ; 1 µm = 10^{-4} cm 0.001 inch = 1 mil = 25.4 µm;
1 bar = 10^6 dyn/cm^2 = 10^5 N/m^2; 1 weber/m^2 = 10^4 gauss = 1 tesla;
1 pascal = 1 N/m^2 = 7.5×10^{-3} torr; 1 erg = 10^{-7} joule = 1 dyn-cm

Figure by MIT OCW.