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

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

$$F = -eE = m_o \frac{dv}{dt} \quad \text{in vacuum}$$
$$F = -eE = m^* \frac{dv}{dt} \quad \text{in solid}$$

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

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

Extrinsic properties
Donors – group V
Acceptors – group III

<table>
<thead>
<tr>
<th>B</th>
<th>C</th>
<th>N</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>Si</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>Ga</td>
<td>Ge</td>
<td>As</td>
<td>Se</td>
</tr>
<tr>
<td>In</td>
<td>Sn</td>
<td>Sb</td>
<td>Te</td>
</tr>
<tr>
<td>Tl</td>
<td>Pb</td>
<td>Bi</td>
<td>Po</td>
</tr>
</tbody>
</table>

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)

\[ g(E) \, dE = \text{density of electron states cm}^{-3} \text{ in the interval } (E, E+dE), \]

units #/eV.cm\(^{-3}\)

\[ g_c(E) \, dE = m_n^* \sqrt{2m_n^*(E - E_c)} / (\pi^2 \hbar^2) \, dE \]

\[ g_v(E) \, dE = m_p^* \sqrt{2m_p^*(E_v - E)} / (\pi^2 \hbar^2) \, dE \]

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

\[ n_i = N_c \exp (E_i - E_c)/kT \]

\[ N_c = 2\{2\pi m_n^* kT/\hbar^2\}^{3/2} = \text{‘effective density of conduction band states’} \]

\(E_i\) is the position of the Fermi level in the intrinsic case.

Similarly for \(N_v\).

Hence

\[ np = n_i^2 \text{ at equilibrium} \]

\[ n_i^2 = N_c N_v \exp (E_v - E_c)/kT = N_c N_v \exp (-E_f)/kT \]

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 \(p \sim N_A\)

\[ E_f - E_i = kT \ln (n/ n_i) = -kT \ln (p/ n_i) \]

\[ \sim kT \ln (N_D / n_i) \text{ or } -kT \ln (N_A / n_i) \]

n-type

p-type
Handout 1

<table>
<thead>
<tr>
<th>Properties</th>
<th>Si</th>
<th>GaAs</th>
<th>SiO₂</th>
<th>Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atoms/cm³, molecules/cm³ x 10²²</td>
<td>5.0</td>
<td>4.42</td>
<td>2.27ₐ</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>diamond</td>
<td>zincblende</td>
<td>amorphous</td>
<td></td>
</tr>
<tr>
<td>Lattice constant (nm)</td>
<td>0.543</td>
<td>0.565</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.33</td>
<td>5.32</td>
<td>2.27ₐ</td>
<td></td>
</tr>
<tr>
<td>Relative dielectric constant, εₚ</td>
<td>11.9</td>
<td>13.1</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>Permittivity, ε = εᵦε₀ (farad/cm) x 10⁻¹²</td>
<td>1.05</td>
<td>1.16</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>Expansion coefficient (dL/LdT) x (10⁻⁶ K)</td>
<td>2.6</td>
<td>6.86</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Specific Heat (joule/g K)</td>
<td>0.7</td>
<td>0.35</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (watt/cm K)</td>
<td>1.48</td>
<td>0.46</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>Thermal diffusivity (cm²/sec)</td>
<td>0.9</td>
<td>0.44</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>Energy Gap (eV)</td>
<td>1.12</td>
<td>1.424</td>
<td>~9</td>
<td>0.67</td>
</tr>
<tr>
<td>Drift mobility (cm²/volt-sec)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>1500</td>
<td>8500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holes</td>
<td>450</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective density of states (cm⁻³) x 10¹⁹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conduction band</td>
<td>2.8</td>
<td>0.047</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valence band</td>
<td>1.04</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrinsic carrier concentration (cm⁻³)</td>
<td>1.45 x 10¹⁰</td>
<td>1.79 x 10⁶</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Properties of Si, GaAs, SiO₂, and Ge at 300 K

Figure by MIT OCW.
## Physical Constants

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

## Useful Combinations

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

## Prefixes

- \( k = \text{kilo} = 10^3 \)
- \( M = \text{mega} = 10^6 \)
- \( G = \text{giga} = 10^9 \)
- \( T = \text{tera} = 10^{12} \)
- \( m = \text{milli} = 10^{-3} \)
- \( \mu = \text{micro} = 10^{-6} \)
- \( n = \text{nano} = 10^{-9} \)
- \( p = \text{pica} = 10^{-12} \)

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

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Figure by MIT OCW.