Characteristics of Semiconductor Materials

Chapter 2: Semiconductor Manufacturing Technology by M. Quirk and J. Serda

Chapter 3.1 and 3.2: Semiconductor Science by Tudor E. Jenkins

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Electron Shells in Atoms

Figure 2.2 Quirk & Serda

Q = 2
P = 10
O = 32
N = 32
M = 18
L = 8
K = 2
Elementary Model of Carbon Atom

Carbon atom: The nucleus contains an equal number of protons (+) and neutrons (6 each). Six electrons (-) orbit around the nucleus.

Figure 2.1 Quirk & Serda
Group IV A Elemental semiconductors

<table>
<thead>
<tr>
<th>Group IVA</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C, Carbon</td>
<td>6</td>
</tr>
<tr>
<td>Si, Silicon</td>
<td>14</td>
</tr>
<tr>
<td>Ge, Germanium</td>
<td>32</td>
</tr>
<tr>
<td>Sn, Tin</td>
<td>50</td>
</tr>
<tr>
<td>Pb, Lead</td>
<td>82</td>
</tr>
</tbody>
</table>

Figure 2.18 Quirk & Serda
Covalent Bonding of Pure Silicon

Silicon atoms share valence electrons to form insulator-like bonds.

Figure 2.19 Quirk & Serda
Crystal Structure of Si and GaAs

Fig. 1.22  (a) Diamond lattice; (b) zinc-blende lattice. In (a) the atoms marked R make up a ‘puckered’ hexagonal ring.
Crystal Structure

Fig. 1.14 The fourteen Bravais lattices.
Classifying Materials

• Conductors
• Insulators
• Semiconductors
Energy Bandgaps

- Insulator: Overlapping bands - little energy is needed for conduction
- Conductor: Overlapping bands - little energy is needed for conduction
- Semiconductor: Overlapping bands - little energy is needed for conduction

Figure 2.4 Quirk & Serda
Energy Band Diagram for III-V Semiconductor

Fig. 3.6 Typical $E-k$ relationship in a III–V semiconductor showing light hole, heavy hole and split-off hole bands. The valence band structure for the elemental semiconductors is similar.
Covalent Bonding in Pure Silicon

Silicon atoms share valence electrons to form insulator-like bonds.

Figure 2.19 Quirk & Serda
Doping of Silicon

Deposition Step

Drive-in & Diffusion Step

diffusion of dopant atoms through silicon

Figure 2.21 Quirk & Serda
# Silicon Dopants

<table>
<thead>
<tr>
<th>Acceptor Impurities</th>
<th>Semiconductor</th>
<th>Donor Impurities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group III (p-type)</strong></td>
<td><strong>Group IV</strong></td>
<td><strong>Group V (n-type)</strong></td>
</tr>
<tr>
<td>Boron 5</td>
<td>Carbon 6</td>
<td>Nitrogen 7</td>
</tr>
<tr>
<td>Aluminum 13</td>
<td>Silicon 14</td>
<td>Phosphorus 15</td>
</tr>
<tr>
<td>Gallium 31</td>
<td>Germanium 32</td>
<td>Arsenic 33</td>
</tr>
<tr>
<td>Indium 49</td>
<td>Tin 50</td>
<td>Antimony 51</td>
</tr>
</tbody>
</table>

*Items underlined are the most commonly used in silicon-based IC manufacturing.*

Figure 2.22 Quirk & Serda
Electrons in n-type Silicon with Phosphorus Dopants

Donor atoms provide excess electrons to form n-type silicon.

Figure 2.23 Quirk & Serda
Conduction in n-type Silicon

Free electrons flow toward positive terminal.

Negative terminal from power supply

Positive terminal from power supply

Figure 2.24 Quirk & Serda
Holes in p-type Silicon with Boron Dopant

Acceptor atoms provide a deficiency of electrons to form p-type silicon.

Figure 2.25 Quirk & Serda
Conduction in p-type Silicon

Positive terminal from voltage supply

Negative terminal from voltage supply

Electron Flow

Hole Flow

+E Electrons flow toward positive terminal

+Holes flow toward negative terminal

Figure 2.26 Quirk & Serda
Impurity States

n-type

p-type

Fig. 3.10 In (a) shallow donor impurities lie above the Fermi level ($E_{F_1}$) and are fully ionized. The addition of some deep acceptor impurities (for example, Zn in Si) is shown at $E_2$. Since they lie below the Fermi level, the acceptor states will be occupied by electrons, reducing the conductivity of this n-type material. (b) shows p-type material. The acceptor impurity levels lie below the Fermi level ($E_{F_2}$) and so are occupied by electrons, that is, have liberated holes in the valence band. Deep donor states (●) will be ionized, their freed electrons recombining with holes in the valence band, thus reducing the density of holes in the valence band.
Density of Impurity States
(for amorphous semiconductor)

*Fig. 3.9* Density of states in an amorphous semiconductor, showing extended states, localized tail states, and defect-induced gap states.
Density of Electrons and Hole in a Semiconductor

Fig. 3.21 Density of electrons and holes in a semiconductor.
How Size affects Resistance

\[ R = \frac{\rho L}{A} \]

Low Resistance

High Resistance

Figure 2.12 Quirk & Serda
Electrical Conductivity and Mobility

- The simplest picture of electrical conductivity and mobility can be understood by considering the electrons in a semiconductor as a classical gas in the body of the material.
- Then using the Maxwell-Boltzmann distribution function we can get the relation,

\[ \frac{1}{2}m \langle v^2 \rangle = \frac{3}{2}kT \]

- At a temperature of 300 K and using free electron mass for ‘m’, we have

\[ \langle v \rangle \approx 10^6 \text{m} \text{s}^{-1} \]

- The random nature of electron velocities means that the time average current that flows is zero.
- On application of an electric field to the semiconductor, the electrons will drift in the opposite direction of the field, so that there is now a net flow of charge and hence a flow of current. Therefore the equation of motion using drift velocity \( v_d \) can be written as:

\[ m \left( \frac{dv_d}{dt} \right) + \frac{mv_d}{\tau} = qE \]
Electrical Conductivity and Mobility (continued)

• The second term in the equation is introduced to prevent ever increasing electron velocity with the electric field on. Therefore electrons are accelerated until a time $\tau$ and then suffer scattering within the system and their velocity randomized.

• In the absence of Electric field the equation becomes:

$$m \left( \frac{dv_d}{dt} \right) + \frac{mv_d}{\tau} = qE$$

• The solution can be written as:

$$mv_d = (mv_d)_0 \exp \left( -\frac{t}{\tau} \right)$$

• The relaxation time represents the tendency of scattering in the semiconductor to return the electron distribution to thermal equilibrium.

• Therefore in the steady state the ‘$d/dt$’ term will not be there.

$$v_d = qE \frac{\tau}{m}$$
Electrical Conductivity and Mobility (continued)

- The current density \( J \) is therefore given as:

\[
J = nqv_d
= \left( \frac{nq^2 \tau}{m} \right) E
\]

- Where \( n \) is the number of electrons per unit volume of the semiconductor. This is Ohm’s Law

\[
J = \left( \frac{nq^2 \tau}{m} \right) E = \sigma E
\]

Or

\[
\sigma = \frac{nq^2 \tau}{m}
\]

- The mobility is expressed as:

\[
\mu = \frac{|v_d|}{|E|} = \frac{e \tau}{m}
\]
Silicon Resistivity vs. Dopant Concentration

Redrawn from *VLSI Fabrication Principles, Silicon and Gallium Arsenide*, John Wiley & Sons, Inc.

Figure 2.27 Quirk & Serda
Cross-section of planar pn-junction

p-type Si  n-type Si

Figure 2.28 Quirk & Serda
Flow of Free Electrons in Copper

Copper atom

<table>
<thead>
<tr>
<th>Shell #</th>
<th>Maximum # e⁻ per shell</th>
<th>Actual # e⁻ per shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>L</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>M</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>N</td>
<td>32</td>
<td>1</td>
</tr>
<tr>
<td>Total #</td>
<td>60</td>
<td>29</td>
</tr>
</tbody>
</table>

Figure 2.11 Quirk & Serda
## Alternative Semiconductor Materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>Ge</th>
<th>GaAs</th>
<th>SiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point (°C)</td>
<td>1412</td>
<td>937</td>
<td>1238</td>
<td>1700</td>
</tr>
<tr>
<td>Atomic Weight</td>
<td>28.09</td>
<td>72.60</td>
<td>144.63</td>
<td>60.08</td>
</tr>
<tr>
<td>Atomic Density (atoms/cm³)</td>
<td>4.99x10²²</td>
<td>4.42x10²²</td>
<td>2.21x10²²</td>
<td>2.3x10²²</td>
</tr>
<tr>
<td>Energy Band Gap (eV)</td>
<td>1.11</td>
<td>0.67</td>
<td>1.40</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 2.3 Quirk & Serda
Resistivity vs. Impurity Concentration for Si and GaAs

![Graph showing resistivity vs. impurity concentration for Si and GaAs](image)

**Fig. 7** Resistivity versus impurity concentration for Si and GaAs.
# Electronic Properties of some Semiconductors

## Electronic Properties of Some Semiconductors

<table>
<thead>
<tr>
<th>Material</th>
<th>Gap energy $E_g$[eV]</th>
<th>Conductivity $\sigma$ $\text{[S/m]}$</th>
<th>Mobility of electrons $\mu_e$ $\text{[m}^2\text{V}^{-1}\text{s}^{-1}]$</th>
<th>Mobility of holes $\mu_h$ $\text{[m}^2\text{V}^{-1}\text{s}^{-1}]$</th>
<th>Work Function (photoelectric) $\phi$[eV]</th>
<th>Effective Mass at 4 K $m^* / m_0$</th>
<th>$m_p^* / m_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (diamond)</td>
<td>5.48</td>
<td>$10^{-12}$</td>
<td>0.18</td>
<td>0.12</td>
<td>4.8</td>
<td>0.2</td>
<td>0.25</td>
</tr>
<tr>
<td>Ge</td>
<td>0.74</td>
<td>2.2</td>
<td>0.39</td>
<td>0.19</td>
<td>4.6</td>
<td>1.64</td>
<td>0.04</td>
</tr>
<tr>
<td>Si</td>
<td>1.17</td>
<td>$9 \times 10^{-4}$</td>
<td>0.15</td>
<td>0.045</td>
<td>3.6</td>
<td>0.98</td>
<td>0.28</td>
</tr>
<tr>
<td>Sn (gray)</td>
<td>0.08</td>
<td>$10^6$</td>
<td>0.14</td>
<td>0.12</td>
<td>4.4</td>
<td>0.19</td>
<td>0.49</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.52</td>
<td>$10^{-6}$</td>
<td>0.85</td>
<td>0.04</td>
<td>0.067</td>
<td>0.023</td>
<td>0.40</td>
</tr>
<tr>
<td>InAs</td>
<td>0.42</td>
<td>$10^4$</td>
<td>3.30</td>
<td>0.046</td>
<td>0.023</td>
<td>0.014</td>
<td>0.40</td>
</tr>
<tr>
<td>InSb</td>
<td>0.23</td>
<td>0.17</td>
<td>8.00</td>
<td>0.125</td>
<td>0.82</td>
<td>0.13</td>
<td>0.60</td>
</tr>
<tr>
<td>GaP</td>
<td>2.34</td>
<td>2.26</td>
<td>0.01</td>
<td>0.007</td>
<td>0.60</td>
<td>1.00</td>
<td>0.45</td>
</tr>
<tr>
<td>IV–IV α-SiC</td>
<td>3.03</td>
<td>2.996</td>
<td>0.04</td>
<td>0.005</td>
<td>0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II–VI ZnO</td>
<td>3.42</td>
<td>3.35</td>
<td>0.02</td>
<td>0.018</td>
<td>0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CdSe</td>
<td>1.85</td>
<td>1.70</td>
<td>0.08</td>
<td></td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Longitudinal effective mass.

* Transverse effective mass.

* Light-hole effective mass.

* Heavy-hole effective mass.
Physical Constants

The International System of Units (SI or mksA System)

In the SI-unit system, essentially four base units, the meter, the kilogram (for the mass), the second, and the ampere are defined. Further base units are the Kelvin, the mole (for the amount of substance), and the Candela (for the luminous intensity). All other units are derived units as shown in the table below. Even though the use of the SI-unit system is highly recommended, other unit systems are still widely used.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Name</th>
<th>Symbol</th>
<th>Expression in terms of Other SI units</th>
<th>SI base units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>Newton</td>
<td>N</td>
<td>kg · m/s²</td>
<td></td>
</tr>
<tr>
<td>Energy, work</td>
<td>Joule</td>
<td>J</td>
<td>N · m</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>Pascal</td>
<td>Pa</td>
<td>kg · m⁻²</td>
<td></td>
</tr>
<tr>
<td>El. charge</td>
<td>Coulomb</td>
<td>C</td>
<td>V/J</td>
<td>A · s</td>
</tr>
<tr>
<td>Power</td>
<td>Watt</td>
<td>W</td>
<td>J/s</td>
<td>kg · m²/s³</td>
</tr>
<tr>
<td>El. potential</td>
<td>Volt</td>
<td>V</td>
<td>W/A</td>
<td>kg · m⁻²/A²·s²</td>
</tr>
<tr>
<td>El. resistance</td>
<td>Ohm</td>
<td>Ω</td>
<td>V/A</td>
<td>kg · m⁻²/A²·s²</td>
</tr>
<tr>
<td>Magn. flux</td>
<td>Weber</td>
<td>Wb</td>
<td>V·s</td>
<td>kg · m⁻²/A·s²</td>
</tr>
<tr>
<td>Magn. field</td>
<td>Tesla</td>
<td>T</td>
<td>Wb/m²</td>
<td>kg · A⁻²</td>
</tr>
<tr>
<td>Inductance</td>
<td>Henry</td>
<td>H</td>
<td>Wb/A</td>
<td>kg · m²/A²·s²</td>
</tr>
<tr>
<td>Capacitance</td>
<td>Farad</td>
<td>F</td>
<td>C/V</td>
<td>A²·s²/kg · m³</td>
</tr>
</tbody>
</table>

Physical Constants (cgs and SI units)

- Mass of electron (Free electron mass): \( m_e = 9.11 \times 10^{-31} \) (kg)
- Charge of electron: \( e = 1.60 \times 10^{-19} \) (C)
- Velocity of light: \( c = 2.998 \times 10^{10} \) (cm/s) = 2.998 \( 10^{8} \) (m/s)
- Planck constant: \( h = 6.626 \times 10^{-27} \) (g · cm²/s) = 4.136 \( 10^{-15} \) (eV · s)
  - \( h = 6.025 \times 10^{-34} \) (J · s)
  - \( h = 1.055 \times 10^{-37} \) (g · cm²/s) = 6.57 \( 10^{-16} \) (eV · s)
- Avogadro constant: \( N_A = 6.025 \times 10^{23} \) (atoms/mol)
- Boltzmann constant: \( k_B = 1.381 \times 10^{-16} \) (erg/K) = 8.616 \( 10^{-3} \) (eV/K)
- Bohr magneton: \( \mu_B = 9.274 \times 10^{-21} \) (erg/Oe) = \( 10^{-7} \) (T · cm²)
- Gas constant: \( R = 8.314 \) (J/mol · K) = 1.986 \( 10^{3} \) (cal/mol · K)

Useful Conversions

- \( 1 \) (eV) = \( 1.60 \times 10^{-13} \) (g · cm²/s) = \( 1.60 \times 10^{-16} \) (kg · m²/s²)
- \( 1 \) (J) = \( 1 \) (kg · m²/s²) = \( 10^{7} \) (erg) = \( 10^{7} \) (g · cm²/s²) = 2.39 \( 10^{14} \) (cal)
- \( 1 \) (Ry) = 13.6 (eV)
- \( 1 \) (J/Cm) = \( 9 \times 10^{14} \) (1/J)
- \( 1 \) (Gm) = \( 9 \times 10^{9} \) (1/A)
- \( 1 \) (C) = \( 1 \) (A · s) = \( 1 \) (J/V)
- \( 1 \) (Å) = \( 10^{-10} \) (m)
- \( 1 \) (torr) = \( 1 \) (mm Hg) = \( 133.3 \) (N/m²) = 133.3 Pa
- \( 1 \) (bar) = \( 10^{5} \) (N/m²) = \( 10^{5} \) Pa
Thank You