Figure 6-1  Lattice structure and energy levels of silicon.  
(a) schematic planar crystal arrangement with thermal breakup of one valent bond resulting in a hole and a moving electron for $T > 0^\circ K$.  
(b) equivalent energy band level representation whereby a hole is created in the valence band $W_V$ and an electron is produced in the conduction band $W_C$. The energy gap between both bands is indicated by $W_g$.  

(a) Planar representation of covalent bonds  
(b) Energy band levels
### Table 6-1 Effective concentrations and effective mass values at $T = 300^\circ$K

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>$m_e^*/m_0$</th>
<th>$m_h^*/m_0$</th>
<th>$N_C$ (cm$^{-3}$)</th>
<th>$N_V$ (cm$^{-3}$)</th>
<th>$n_i$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon (Si)</td>
<td>1.08</td>
<td>0.56</td>
<td>2.8×10$^{19}$</td>
<td>1.04×10$^{19}$</td>
<td>1.45×10$^{10}$</td>
</tr>
<tr>
<td>Germanium (Ge)</td>
<td>0.55</td>
<td>0.37</td>
<td>1.04×10$^{19}$</td>
<td>6.0×10$^{18}$</td>
<td>2.4×10$^{13}$</td>
</tr>
<tr>
<td>Gallium Arsenide (GaAs)</td>
<td>0.067</td>
<td>0.48</td>
<td>4.7×10$^{17}$</td>
<td>7.0×10$^{18}$</td>
<td>1.79×10$^{6}$</td>
</tr>
</tbody>
</table>
**Figure 6-2** Conductivity of Si, Ge, GaAs in the range from –50°C to 250°C.
Figure 6-3  Lattice structure and energy band model for (a) intrinsic, (b) n-type, and (c) p-type semiconductors at no thermal energy. $W_D$ and $W_A$ are donor and acceptor energy levels.
Figure 6-4  Current flow in the pn-junction
Figure 6-5  The $pn$-junction with abrupt charge carrier transition in the absence of an externally applied voltage.

(a) $pn$-junction with space charge extent

(b) Acceptor and donor concentrations

(c) Polarity of charge density distribution

(d) Electric field distribution
Figure 6-5  The $pn$-junction with abrupt charge carrier transition in the absence of an externally applied voltage. (Continued)
Figure 6-6  External voltage applied to the \textit{pn}-junction in reverse and forward directions.

(a) Reverse biasing \((V_A < 0)\)  \hspace{1cm} (b) Forward biasing \((V_A > 0)\)
Figure 6-7  The pn-junction capacitance as a function of applied voltage.
Figure 6-8  Current-voltage behavior of $pn$-junction based on Shockley equation.
Figure 6-9  Metal electrode in contact with $p$-semiconductor.
Metal and semiconductor do not interact

Metal-semiconductor contact

Figure 6-10  Energy-band diagram of Schottky contact, (a) before and (b) after contact.
Table 6-2  Work function potentials of some metals

<table>
<thead>
<tr>
<th>Material</th>
<th>Work function potential, ( V_M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver (Ag)</td>
<td>4.26 V</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>4.28 V</td>
</tr>
<tr>
<td>Gold (Au)</td>
<td>5.1 V</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>4.5 V</td>
</tr>
<tr>
<td>Molybdenum (Mo)</td>
<td>4.6 V</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>5.15 V</td>
</tr>
<tr>
<td>Palladium (Pd)</td>
<td>5.12 V</td>
</tr>
<tr>
<td>Platinum (Pt)</td>
<td>5.65 V</td>
</tr>
<tr>
<td>Titanium (Ti)</td>
<td>4.33 V</td>
</tr>
</tbody>
</table>
Figure 6-11  Cross-sectional view of Si Schottky diode.
Figure 6-12  Circuit model of typical Schottky diode.
Figure 6-13  Schottky diode with additional isolation ring suitable for very-high-frequency applications.
Figure 6-14  PIN diode construction.
Figure 6-15  PIN diode in series connection.
Figure 6-16  Attenuator circuit with biased PIN diode in series and shunt configurations.
Figure 6-17  Transducer loss of series connected PIN diode under forward bias condition. The diode behaves as a resistor.
Figure 6-18  Transducer loss of series connected PIN diode under reverse bias condition. The diode behaves as a capacitor.
Figure 6-19  Simplified electric circuit model and capacitance behavior of varactor diode.
Figure 6-20  Pulse generation with a varactor diode.
Figure 6-21 IMPATT diode behavior.
Figure 6-22  Applied voltage, ionization current, and total current of an IMPATT diode.
Figure 6-23  Electric circuit representation for the IMPATT diode.
Figure 6-24  Tunnel diode and its band energy representation.
(a) I-V curve of tunnel diode. At high positive biasing voltages the corresponding current of the tunnel diode approaches the current of the conventional pn-junction diode.

(b) Negative current flow for $V_A < 0$

(c) No current flow for $V_A = 0$

(d) Positive tunneling current, $0 < V_A < V_{\text{diff}}$

(e) Positive current flow for $V_A > V_{\text{diff}}$

Figure 6-25  Current-voltage behavior of the tunnel diode and comparison with energy band structure.
Figure 6-26  Electric circuit representation of a tunnel diode.
Figure 6-27  Tunnel diode circuit for amplification/oscillation behavior.
Figure 6-28  Interdigitated structure of high-frequency BJT.
Figure 6-29  Cross-sectional view of a GaAs heterojunction bipolar transistor involving a GaAlAs-GaAs interface.
Figure 6-30  *npn* transistor: (a) structure with electrical charge flow under forward active mode of operation, (b) transistor symbol with voltage and current directions, and (c) diode model.
Biasing and input, output characteristics of an npn BJT.

(a) Biasing circuit for npn BJT in common-emitter configuration

(b) Input characteristic of transistor

(c) Output characteristic of transistor

Figure 6-31  Biasing and input, output characteristics of an npn BJT.
<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Emitter (n-type)</th>
<th>Base (p-type)</th>
<th>Collector (n-type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doping level</td>
<td>$N_D^E$</td>
<td>$N_A^B$</td>
<td>$N_D^C$</td>
</tr>
<tr>
<td>Minority carrier concentration in thermal equilibrium</td>
<td>$p_{n_0}^E = n_i^2 / N_D^E$</td>
<td>$p_{p_0}^B = n_i^2 / N_A^B$</td>
<td>$p_{n_0}^C = n_i^2 / N_D^C$</td>
</tr>
<tr>
<td>Majority carrier concentration in thermal equilibrium</td>
<td>$n_{n_0}^E$</td>
<td>$p_{p_0}^B$</td>
<td>$n_{n_0}^C$</td>
</tr>
<tr>
<td>Spatial extent</td>
<td>$d_E$</td>
<td>$d_B$</td>
<td>$d_C$</td>
</tr>
</tbody>
</table>
Figure 6-32  Minority carrier concentrations in forward active BJT.
Figure 6-33  Reverse active mode of BJT.
Figure 6-34  Transition frequency as a function of collector current for the 17 GHz npn wideband transistor BFG403W (courtesy of Philips Semiconductors).
Figure 6-35  Current gain $\beta = \alpha_F / (1 - \alpha_F)$ as a function of collector current for various junction temperatures at a fixed $V_{CE}$. 
Figure 6-36  Typical base current as a function of base-emitter voltage for various junction temperatures at a fixed $V_{CE}$. 
Figure 6-37  Thermal equivalent circuit of BJT.
Figure 6-38  Operating domain of BJT in active mode with breakdown mechanisms.
Figure 6-39  Construction of (a) MISFET, (b) JFET, and (c) MESFET. The shaded areas depict the space charge domains.
(a) Operation in the linear region.  
(b) Operation in the saturation region.

**Figure 6-40** Functionality of MESFET for different drain-source voltages.
Figure 6-41  Transfer and output characteristics of an $n$-channel MESFET.
Figure 6-42  Drain current versus $V_{GS}$ computed using the exact and the approximate equations (6.87) and (6.88).
Figure 6-43  Drain current as a function of applied drain-source voltage for different gate-source biasing conditions.
Figure 6-44  Typical maximum output characteristics and three operating points of MESFET.
Figure 6-45  Generic heterostructure of a depletion-mode HEMT.
Figure 6-46  Energy band diagram of GaAlAs-GaAs interface for an HEMT.
Figure 6-47  Drain current in a GaAs HEMT.