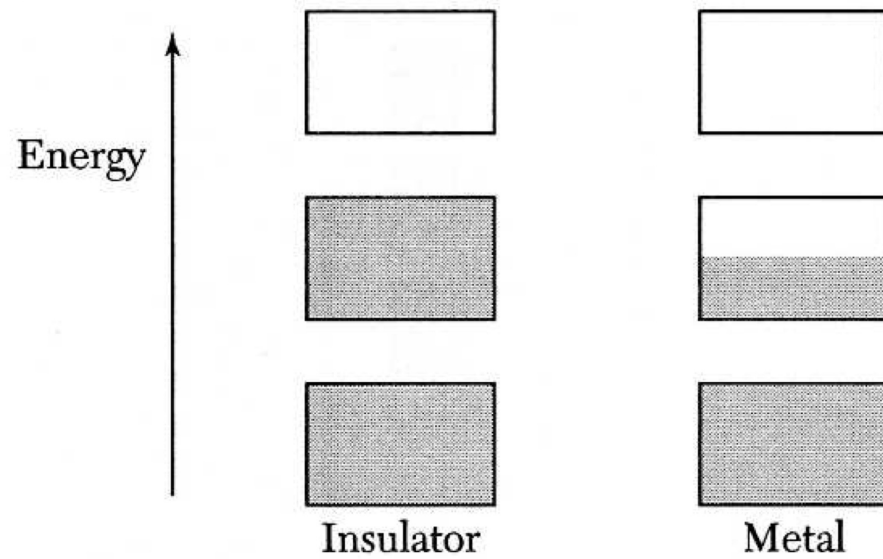


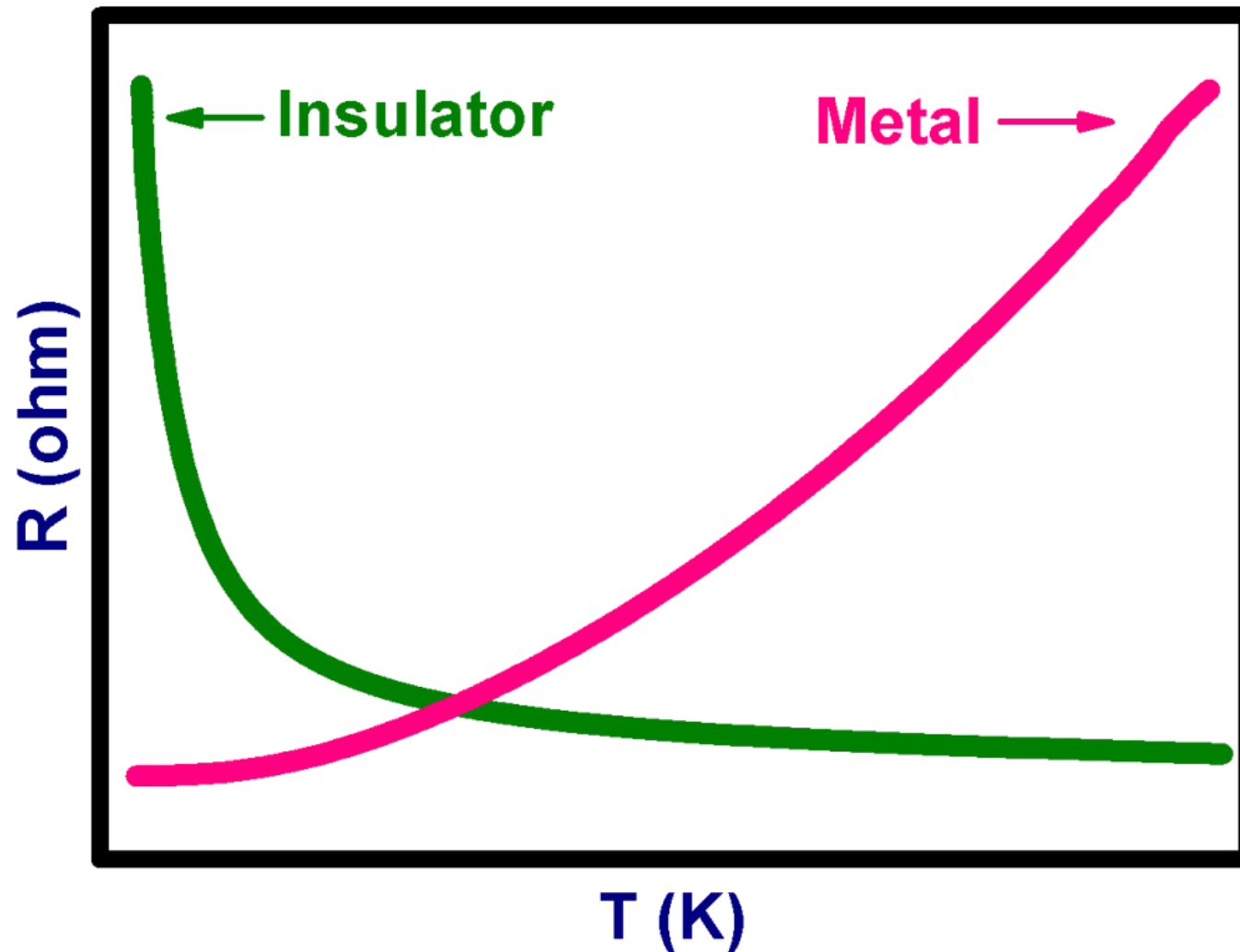
| #  | Dates | Title                        | Exercise       | (1=easy,<br>10=hard) | <b>Tasks</b>         |
|----|-------|------------------------------|----------------|----------------------|----------------------|
| 1  | 22.2  | Introduction                 | VESTA          | <b>2-3</b>           | Read Chap. 1         |
| 2  | 01.3  | Crystal structures           | Daniel - info  | <b>4</b>             | Read Chap. 2, Ex. 1  |
| 3  | 08.03 | Reciprocal space             | Discuss Ex. 1  | <b>6</b>             | Read Chap. 2, Ex. 2  |
| 4  | 15.03 | Scattering Theory            | Discuss Ex. 2  | <b>8-9</b>           | Read Chap. 3, Ex. 3  |
| 5  | 22.03 | Crystal bindings             | Discuss Ex. 3  | <b>5</b>             | Read Chap. 4, Ex. 4  |
| 6  | 29.03 | Phonons                      | Discuss Ex. 4  | <b>5-6</b>           | Read Chap. 5, Ex. 5  |
| 7  | 05.04 | Thermal properties           | Discuss Ex. 5  | <b>5-6</b>           | Read Chap. 6, Ex. 6  |
| 8  | 12.04 | Electron gasses, $C_{el}$    | Discuss Ex. 6  | <b>5-6</b>           | Read Chap. 7, Ex. 7  |
| -- | 19.04 | EASTER HOLIDAY               | -----          | <b>0</b>             | <b>RECAP</b>         |
| 9  | 26.04 | Electronic band struc.       | Discuss Ex. 7  | <b>5-6</b>           | Read Chap. 8, Ex. 8  |
| 10 | 03.05 | Semi-conductors              | Discuss Ex. 8  | <b>6</b>             | Read Chap. 9, Ex. 9  |
| 11 | 10.05 | Fermi surfaces & Metals - I  | Discuss Ex. 9  | <b>8</b>             | Read Chap. 9, Ex. 10 |
| 12 | 17.05 | Fermi surfaces & Metals - II | Discuss Ex. 10 | <b>8</b>             | Read Chap. 9, Ex. 11 |
| 13 | 24.05 | Guest lecture                | Discuss Ex. 11 | --                   |                      |
| 14 | 31.05 | Repetition                   |                | <b>4</b>             |                      |

| #  | Dates | Title                        | Tasks   |
|----|-------|------------------------------|---|
| 10 | 03.05 | Semi-conductors              | <p>Read Chap. 6: Motion in magnetic fields p. 163-167</p> <p>Read Chap. 9: Introduction to Fermi surfaces p. 235-244</p> <p>Read Chap. 9: Experimental methods in FS studies p. 255-265</p> |
| 11 | 10.05 | Fermi surfaces & Metals - I  | <p>Read Chap. 9: Experimental methods in FS studies p. 255-265</p>  |
| 12 | 17.05 | Fermi surfaces & Metals - II | <p>Read Chap. 9 : Calculation of energy bands 244 -255<br/>(Perhaps an extra exercise)</p>  |
| 13 | 24.05 | Guest lecture                |   |
| 14 | 31.05 | Repetition                   |   |

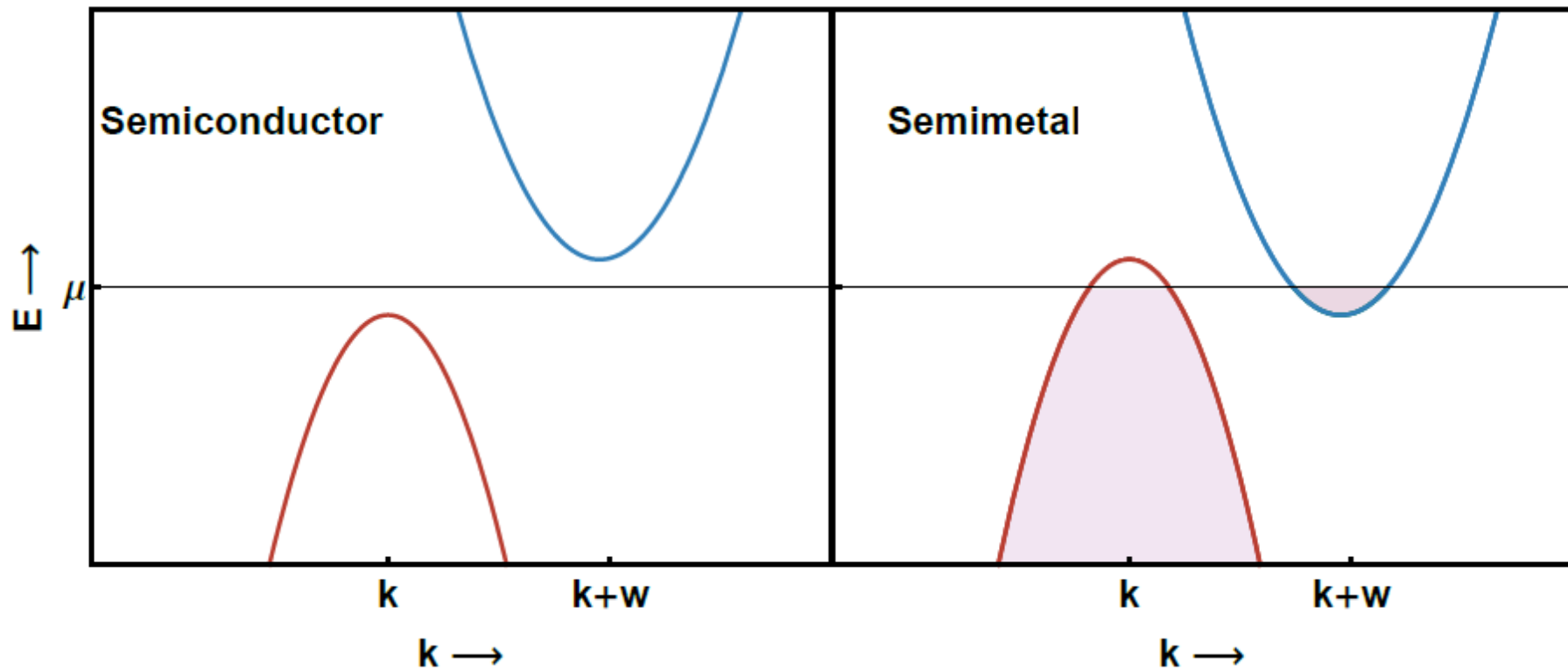
# Metals & Insulators



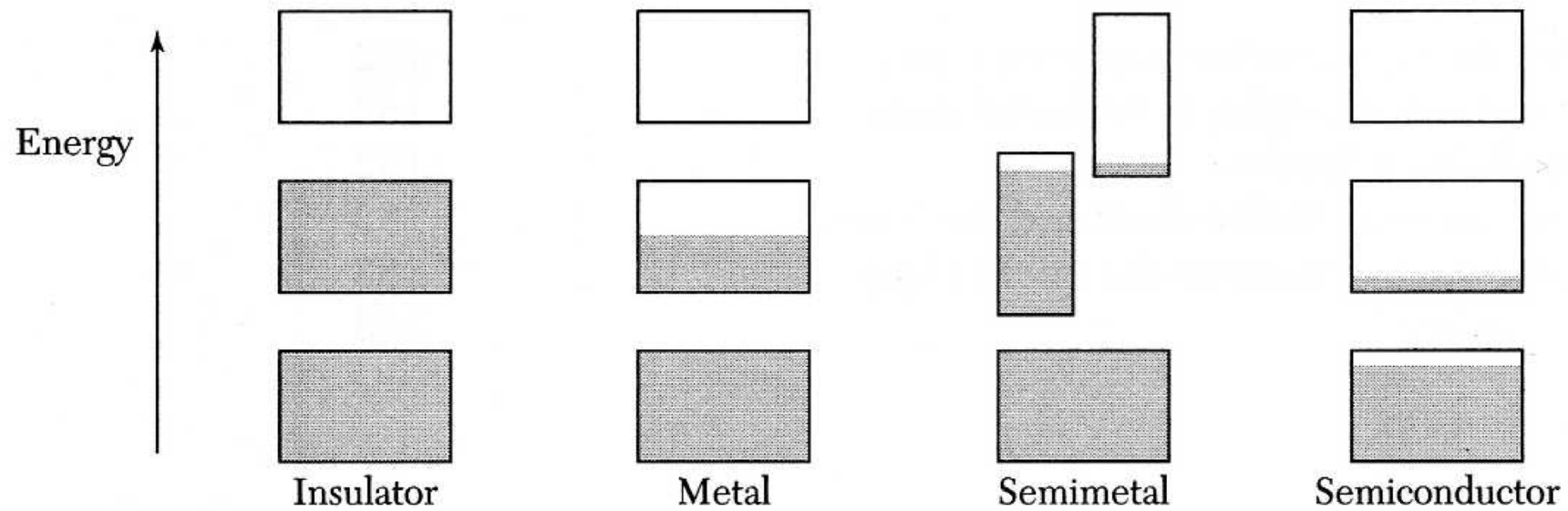
# Metals and insulators: Resistivity



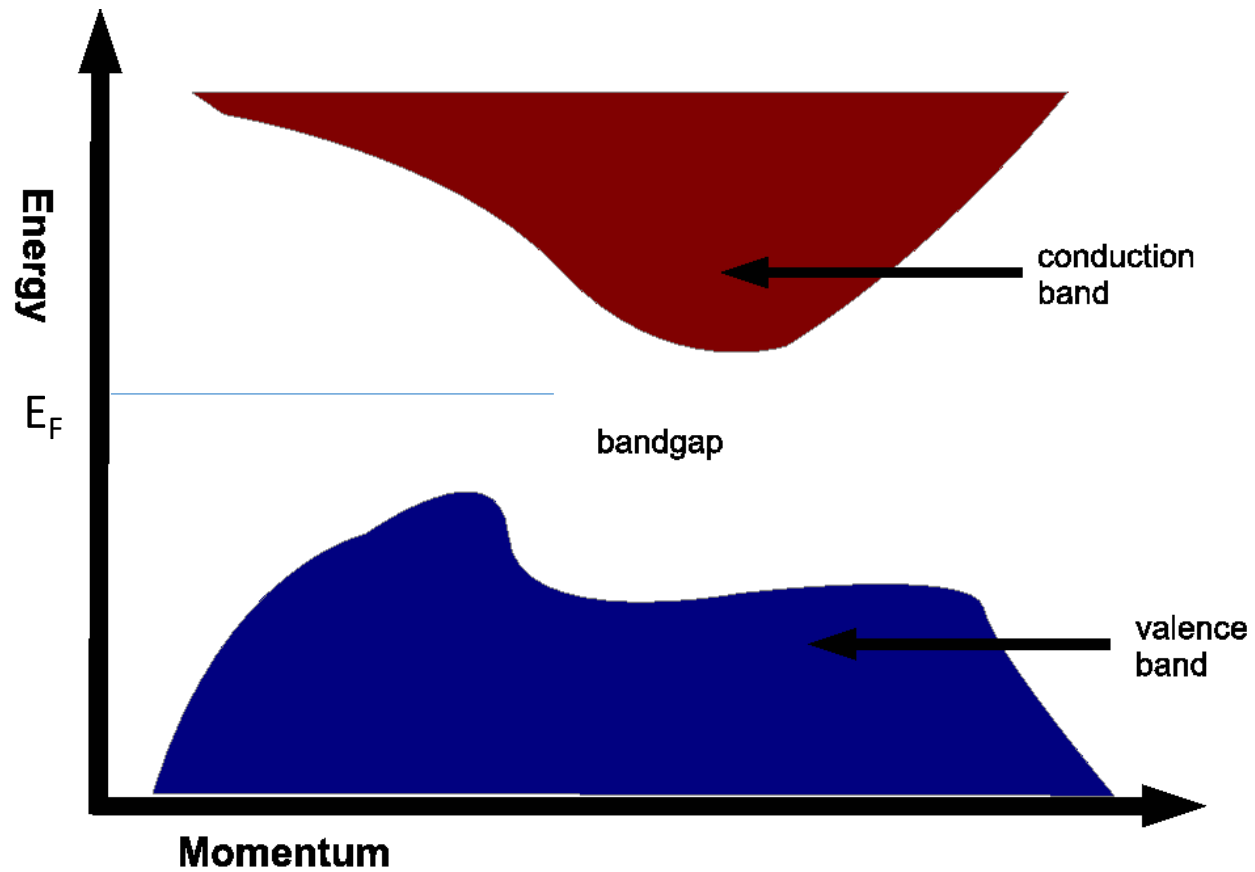
# Semimetals & Semiconductors



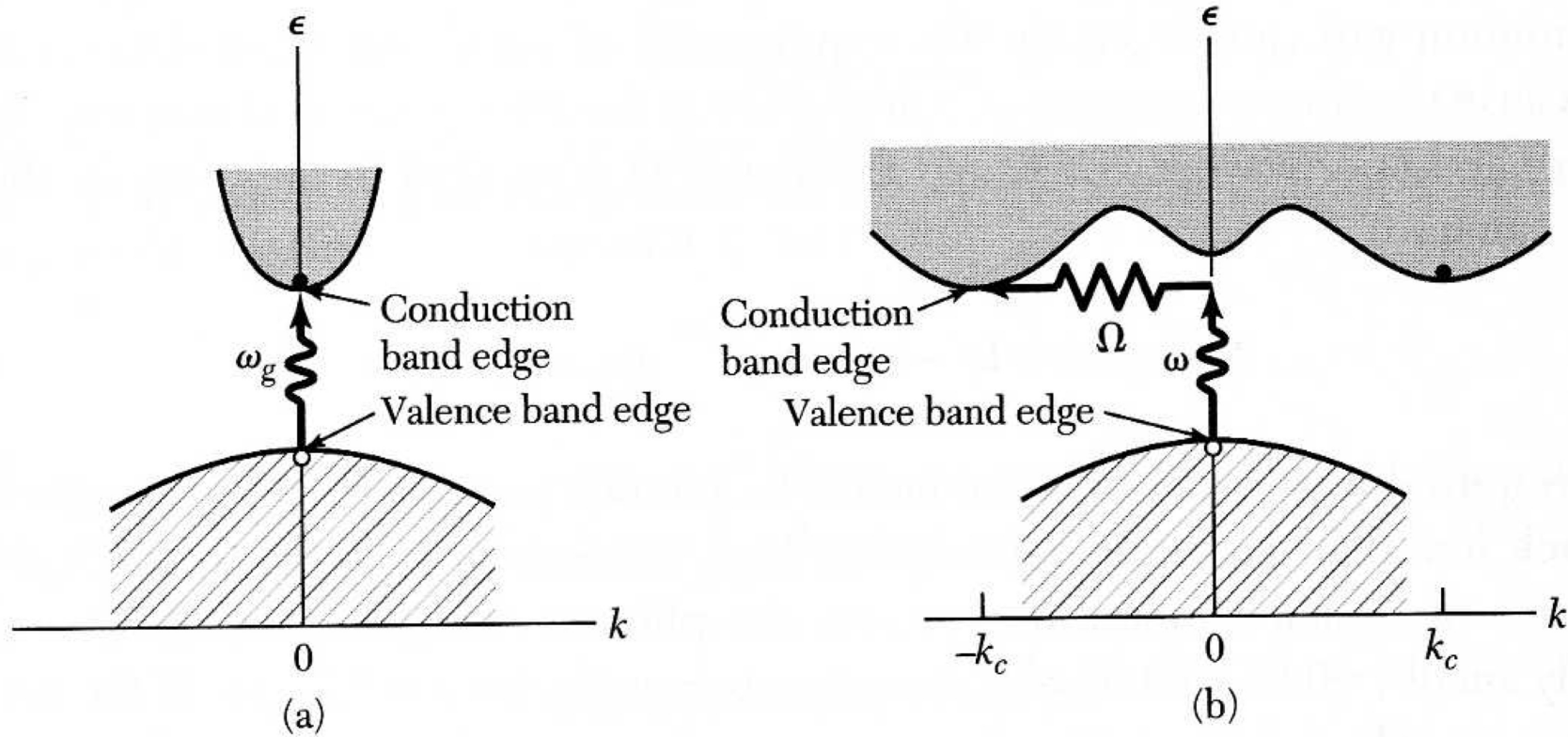
# Semimetals & Semiconductors



# Valence and conduction band



# Direct and indirect gap





# Semiconductor gaps versus $k_B T$

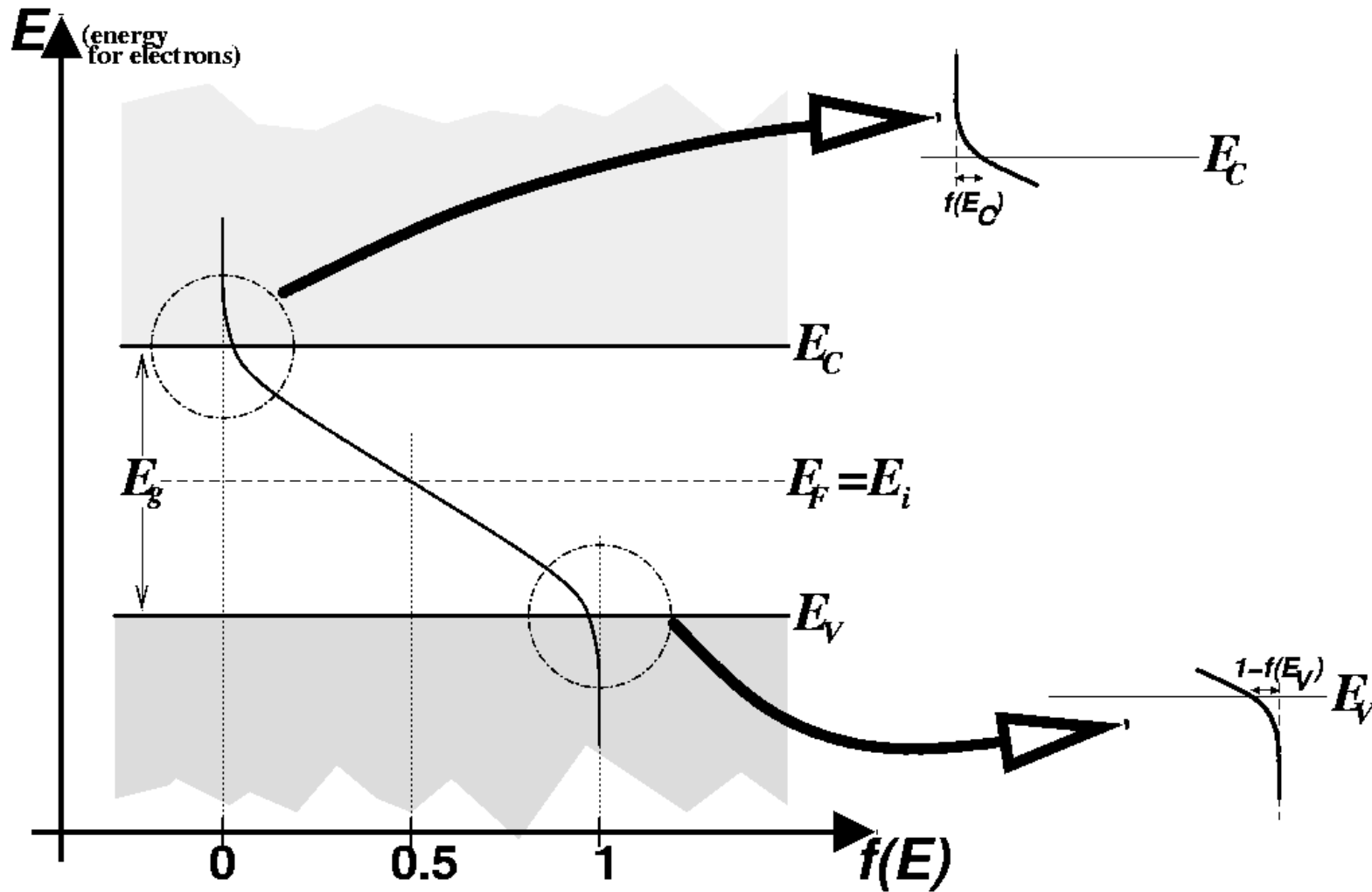
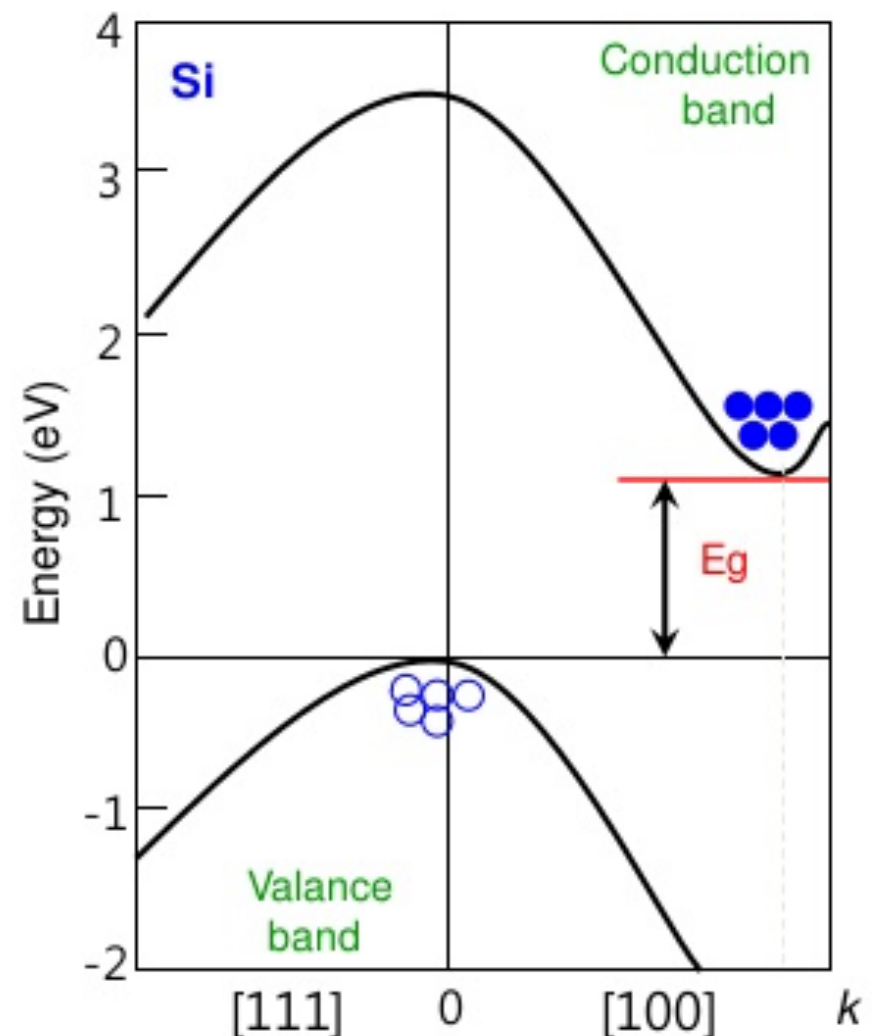
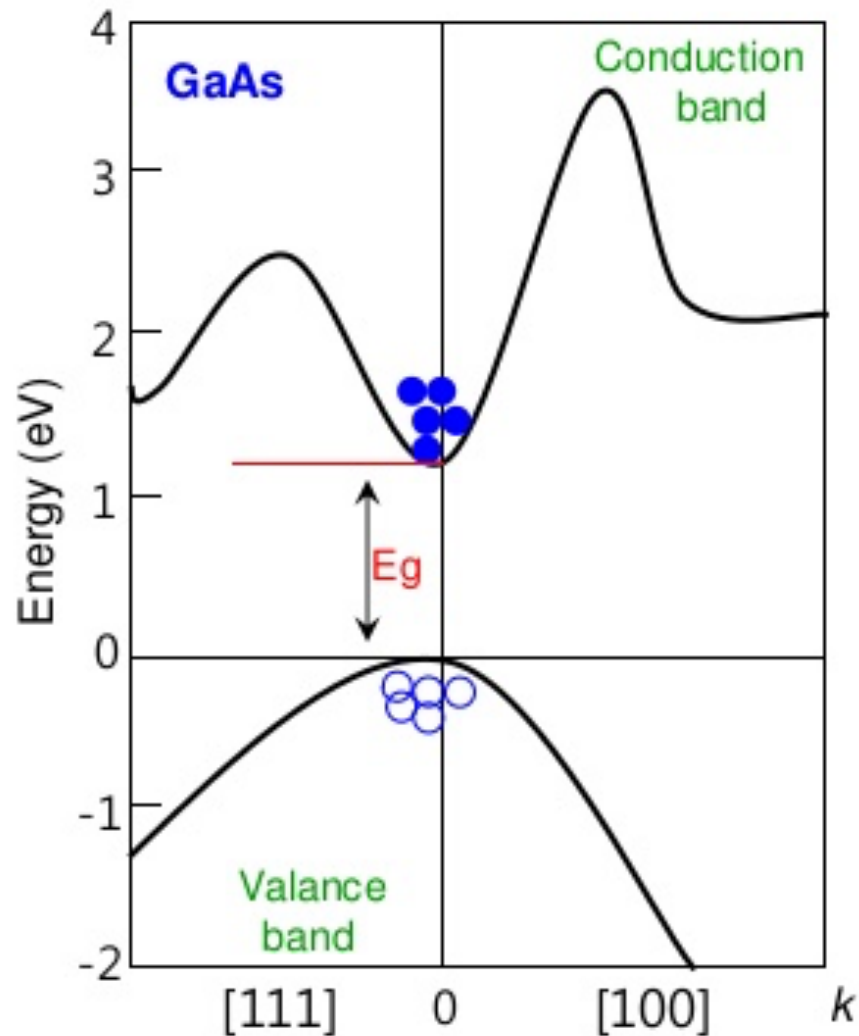


Figure 4:

## Band Structure of Semiconductors



Energy band structures of **GaAs** and **Si**

# Semiconductor gaps

**Table 1 Energy gap between the valence and conduction bands**  
(*i* = indirect gap; *d* = direct gap)

| Crystal     | Gap      | $E_g$ , eV |       | Crystal           | Gap      | $E_g$ , eV |           |
|-------------|----------|------------|-------|-------------------|----------|------------|-----------|
|             |          | 0 K        | 300 K |                   |          | 0 K        | 300 K     |
| Diamond     | <i>i</i> | 5.4        |       | SiC(hex)          | <i>i</i> | 3.0        | —         |
| Si          | <i>i</i> | 1.17       | 1.11  | Te                | <i>d</i> | 0.33       | —         |
| Ge          | <i>i</i> | 0.744      | 0.66  | HgTe <sup>a</sup> | <i>d</i> | -0.30      |           |
| $\alpha$ Sn | <i>d</i> | 0.00       | 0.00  | PbS               | <i>d</i> | 0.286      | 0.34–0.37 |
| InSb        | <i>d</i> | 0.23       | 0.17  | PbSe              | <i>i</i> | 0.165      | 0.27      |
| InAs        | <i>d</i> | 0.43       | 0.36  | PbTe              | <i>i</i> | 0.190      | 0.29      |
| InP         | <i>d</i> | 1.42       | 1.27  | CdS               | <i>d</i> | 2.582      | 2.42      |
| GaP         | <i>i</i> | 2.32       | 2.25  | CdSe              | <i>d</i> | 1.840      | 1.74      |
| GaAs        | <i>d</i> | 1.52       | 1.43  | CdTe              | <i>d</i> | 1.607      | 1.44      |
| GaSb        | <i>d</i> | 0.81       | 0.68  | SnTe              | <i>d</i> | 0.3        | 0.18      |
| AlSb        | <i>i</i> | 1.65       | 1.6   | Cu <sub>2</sub> O | <i>d</i> | 2.172      | —         |

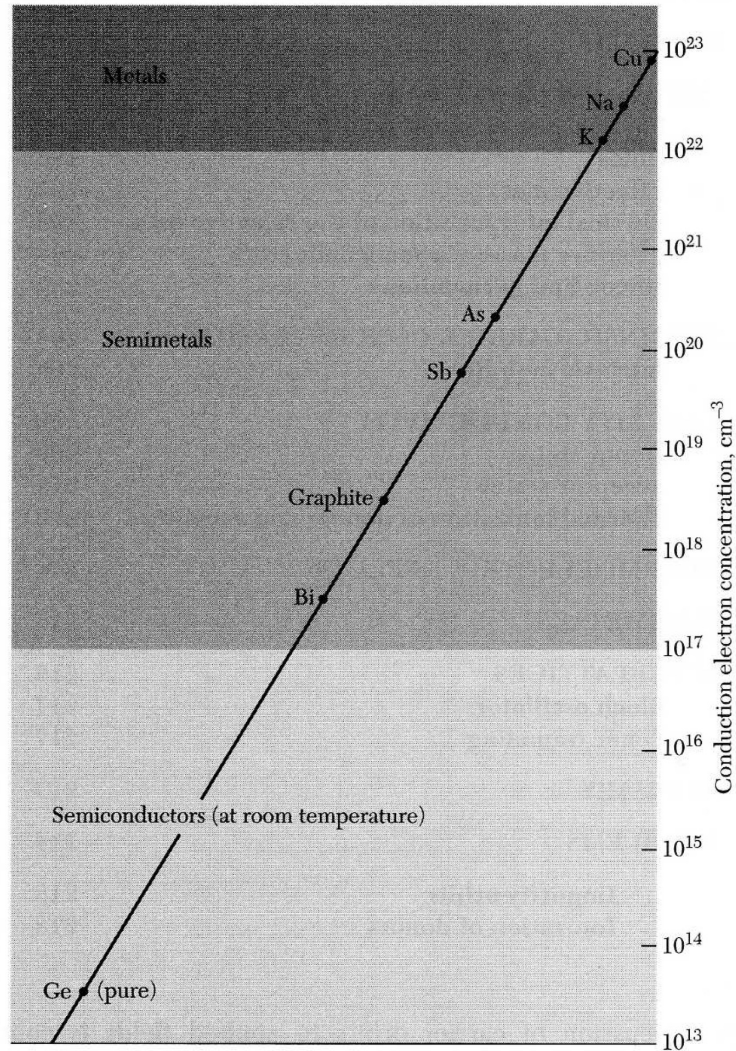
<sup>a</sup>HgTe is a semimetal; the bands overlap.

# Electronic masses

| Crystal           | Electron<br>$m_e/m$ |
|-------------------|---------------------|
| InSb              | 0.015               |
| InAs              | 0.026               |
| InP               | 0.073               |
| GaSb              | 0.047               |
| GaAs              | 0.066               |
| Cu <sub>2</sub> O | 0.99                |

Reading Kittel carefully,  
following notation is adopted.  
 $m$  = is the free electron mass.  
 $m_e$  = effective crystal electron mass

# Conduction Electron Concentration



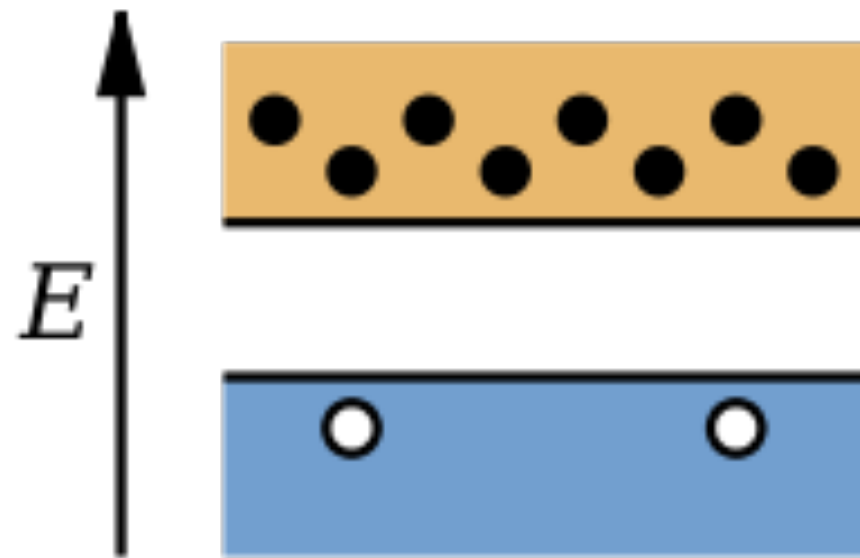
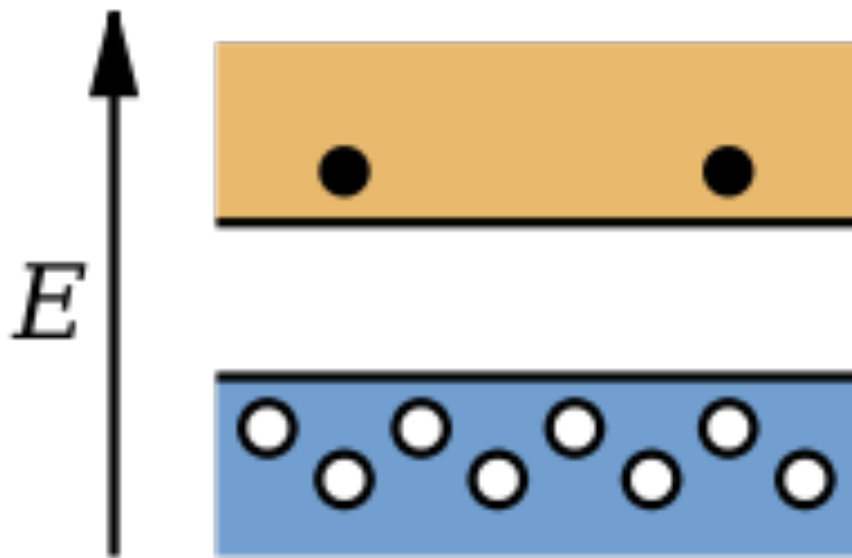
**Figure 1** Carrier concentrations for metals, semimetals, and semiconductors. The semiconductor range may be extended upward by increasing the impurity concentration, and the range can be extended downward to merge eventually with the insulator range.

# Electronic mobility

**Table 3 Carrier mobilities at room temperature, in  $\text{cm}^2/\text{V}\cdot\text{s}$**

| Crystal | Electrons | Holes | Crystal     | Electrons | Holes |
|---------|-----------|-------|-------------|-----------|-------|
| Diamond | 1800      | 1200  | GaAs        | 8000      | 300   |
| Si      | 1350      | 480   | GaSb        | 5000      | 1000  |
| Ge      | 3600      | 1800  | PbS         | 550       | 600   |
| InSb    | 800       | 450   | PbSe        | 1020      | 930   |
| InAs    | 30000     | 450   | PbTe        | 2500      | 1000  |
| InP     | 4500      | 100   | AgCl        | 50        | —     |
| AlAs    | 280       | —     | KBr (100 K) | 100       | —     |
| AlSb    | 900       | 400   | SiC         | 100       | 10–20 |

# n- and p-type semiconductors



# Doping – Performance Enhancement





# Semiconductor Materials

|                                       |  |  |  |                                       |   |  |  |   |  |                                       |                                       |   |                                  |                                      |  |                                      |                                     |  |                                   |  |                                    |                                       |                                    |
|---------------------------------------|--|--|--|---------------------------------------|---|--|--|---|--|---------------------------------------|---------------------------------------|---|----------------------------------|--------------------------------------|--|--------------------------------------|-------------------------------------|--|-----------------------------------|--|------------------------------------|---------------------------------------|------------------------------------|
| hydrogen<br>1<br><b>H</b><br>1.0079   |  |  |  |                                       |   |  |  |   |  |                                       |                                       |   |                                  |                                      |  |                                      | helium<br>2<br><b>He</b><br>4.0026  |  |                                   |  |                                    |                                       |                                    |
| lithium<br>3<br><b>Li</b><br>6.941    | beryllium<br>4<br><b>Be</b><br>9.0122  |  |  |                                       |   |  |  |   |  |                                       |                                       |   |                                  |                                      |  |                                      |                                     | boron<br>5<br><b>B</b><br>10.811       | carbon<br>6<br><b>C</b><br>12.011 | nitrogen<br>7<br><b>N</b><br>14.007    | oxygen<br>8<br><b>O</b><br>15.999  | fluorine<br>9<br><b>F</b><br>18.998   | neon<br>10<br><b>Ne</b><br>20.180  |
| sodium<br>11<br><b>Na</b><br>22.990   | magnesium<br>12<br><b>Mg</b><br>24.305 |  |  |                                       |   |  |  |   |  |                                       |                                       |   |                                  |                                      |  |                                      |                                     | aluminium<br>13<br><b>Al</b><br>26.982 | <b>Si</b><br>14<br>28.086         | phosphorus<br>15<br><b>P</b><br>30.974 | sulfur<br>16<br><b>S</b><br>32.065 | chlorine<br>17<br><b>Cl</b><br>35.453 | argon<br>18<br><b>Ar</b><br>39.948 |
| potassium<br>19<br><b>K</b><br>39.098 | calcium<br>20<br><b>Ca</b><br>40.078   | scandium<br>21<br><b>Sc</b><br>44.956  | titanium<br>22<br><b>Ti</b><br>47.867      | vanadium<br>23<br><b>V</b><br>50.942  | chromium<br>24<br><b>Cr</b><br>51.996   | manganese<br>25<br><b>Mn</b><br>54.938 | iron<br>26<br><b>Fe</b><br>55.845      | cobalt<br>27<br><b>Co</b><br>58.933     | nickel<br>28<br><b>Ni</b><br>58.693    | copper<br>29<br><b>Cu</b><br>63.546   | zinc<br>30<br><b>Zn</b><br>65.39      | <b>Ga</b><br>31<br>69.723                 | <b>Ge</b><br>32<br>72.64         | <b>As</b><br>33<br>74.922            | selenium<br>34<br><b>Se</b><br>78.96   | bromine<br>35<br><b>Br</b><br>79.904 | krypton<br>36<br><b>Kr</b><br>83.80 |  |                                   |  |                                    |                                       |                                    |
| rubidium<br>37<br><b>Rb</b><br>85.468 | strontium<br>38<br><b>Sr</b><br>87.62  | yttrium<br>39<br><b>Y</b><br>88.906    | zirconium<br>40<br><b>Zr</b><br>91.224     | niobium<br>41<br><b>Nb</b><br>92.906  | molybdenum<br>42<br><b>Mo</b><br>95.94  | technetium<br>43<br><b>Tc</b><br>[98]  | ruthenium<br>44<br><b>Ru</b><br>101.07 | rhodium<br>45<br><b>Rh</b><br>102.91    | palladium<br>46<br><b>Pd</b><br>106.42 | silver<br>47<br><b>Ag</b><br>107.87   | cadmium<br>48<br><b>Cd</b><br>112.41  | <b>In</b><br>49<br>114.82                 | <b>Sn</b><br>50<br>118.71        | <b>Sb</b><br>51<br>121.76            | tellurium<br>52<br><b>Te</b><br>127.60 | iodine<br>53<br><b>I</b><br>126.90   | xenon<br>54<br><b>Xe</b><br>131.29  |  |                                   |  |                                    |                                       |                                    |
| caesium<br>55<br><b>Cs</b><br>132.91  | barium<br>56<br><b>Ba</b><br>137.33    | lanthanum<br>57<br><b>La</b><br>174.97 | hafnium<br>72<br><b>Hf</b><br>178.49       | tantalum<br>73<br><b>Ta</b><br>180.95 | wolfram<br>74<br><b>W</b><br>183.84     | rhenium<br>75<br><b>Re</b><br>186.21   | osmium<br>76<br><b>Os</b><br>190.23    | iridium<br>77<br><b>Ir</b><br>192.22    | platinum<br>78<br><b>Pt</b><br>195.08  | gold<br>79<br><b>Au</b><br>196.97     | mercury<br>80<br><b>Hg</b><br>200.59  | thallium<br>81<br><b>Tl</b><br>204.38     | lead<br>82<br><b>Pb</b><br>207.2 | bismuth<br>83<br><b>Bi</b><br>208.98 | polonium<br>84<br><b>Po</b><br>[209]   | astatine<br>85<br><b>At</b><br>[210] | radon<br>86<br><b>Rn</b><br>[222]   |  |                                   |  |                                    |                                       |                                    |
| francium<br>87<br><b>Fr</b><br>[223]  | radium<br>88<br><b>Ra</b><br>[226]     | actinium<br>89<br><b>Ac</b><br>[227]   | rutherfordium<br>104<br><b>Rf</b><br>[261] | dubnium<br>105<br><b>Db</b><br>[262]  | seaborgium<br>106<br><b>Sg</b><br>[266] | bohrium<br>107<br><b>Bh</b><br>[264]   | hassium<br>108<br><b>Hs</b><br>[269]   | meitnerium<br>109<br><b>Mt</b><br>[268] | ununnium<br>110<br><b>Uun</b><br>[271] | ununium<br>111<br><b>Uuu</b><br>[272] | unubium<br>112<br><b>Uub</b><br>[277] | ununquadium<br>114<br><b>Uuq</b><br>[289] |                                  |                                      |  |                                      |                                     |  |                                   |  |                                    |                                       |                                    |

\* Lanthanide series

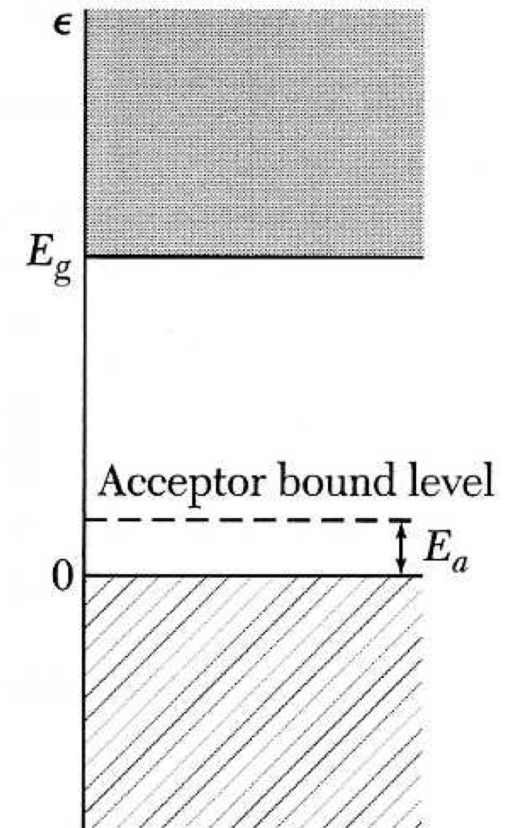
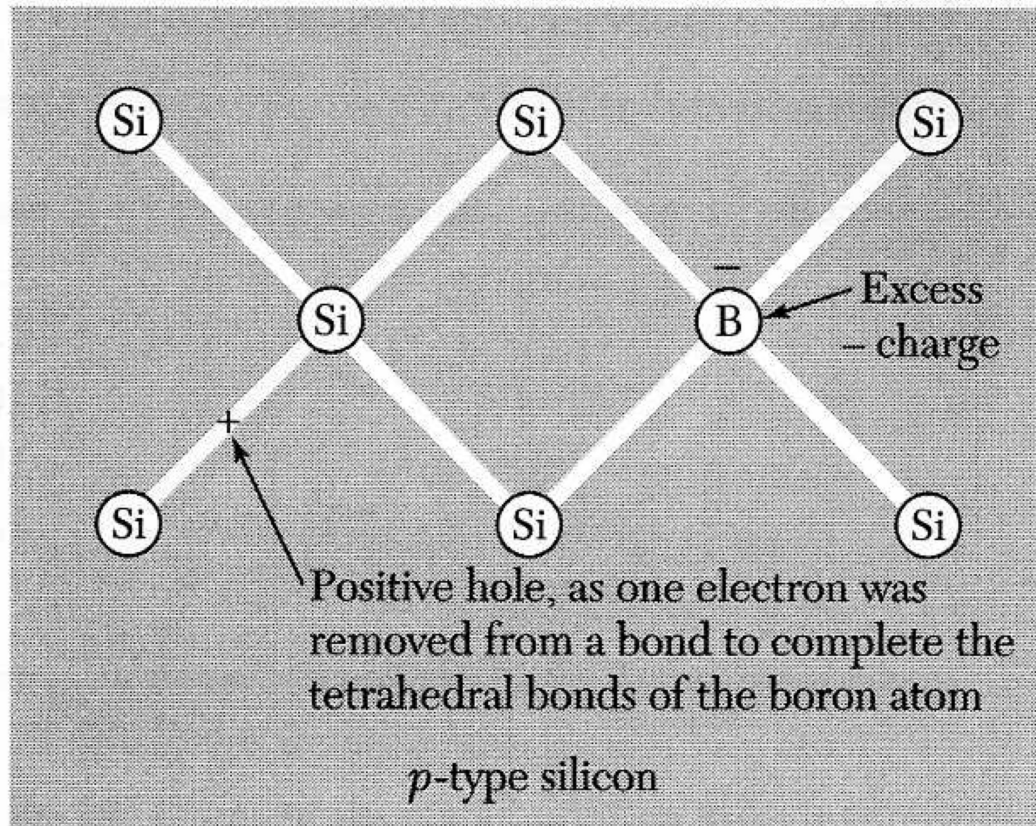
|  |                                      |   |  |  |                                       |                                       |   |                                       |   |   |                                      |  |  |
|--|--------------------------------------|---|--|--|---------------------------------------|---------------------------------------|---|---------------------------------------|---|---|--------------------------------------|--|--|
| lanthanum<br>57<br><b>La</b><br>138.91 | cerium<br>58<br><b>Ce</b><br>140.12  | praseodymium<br>59<br><b>Pr</b><br>140.91 | neodymium<br>60<br><b>Nd</b><br>144.24 | promethium<br>61<br><b>Pm</b><br>[145] | samarium<br>62<br><b>Sm</b><br>150.36 | europium<br>63<br><b>Eu</b><br>151.96 | gadolinium<br>64<br><b>Gd</b><br>157.25 | terbium<br>65<br><b>Tb</b><br>158.93  | dysprosium<br>66<br><b>Dy</b><br>162.50 | holmium<br>67<br><b>Ho</b><br>164.93    | erbium<br>68<br><b>Er</b><br>167.26  | thulium<br>69<br><b>Tm</b><br>168.93     | ytterbium<br>70<br><b>Yb</b><br>173.04 |
| actinium<br>89<br><b>Ac</b><br>[227]   | thorium<br>90<br><b>Th</b><br>232.04 | protactinium<br>91<br><b>Pa</b><br>231.04 | uranium<br>92<br><b>U</b><br>238.03    | neptunium<br>93<br><b>Np</b><br>[237]  | plutonium<br>94<br><b>Pu</b><br>[244] | americium<br>95<br><b>Am</b><br>[243] | curium<br>96<br><b>Cm</b><br>[247]      | berkelium<br>97<br><b>Bk</b><br>[247] | californium<br>98<br><b>Cf</b><br>[251] | einsteinium<br>99<br><b>Es</b><br>[252] | fermium<br>100<br><b>Fm</b><br>[257] | mendelevium<br>101<br><b>Md</b><br>[258] | nobelium<br>102<br><b>No</b><br>[259]  |

\*\* Actinide series

Diamond-type semiconductors

III – V compounds (GaAs, InSb)

# Hole - doping

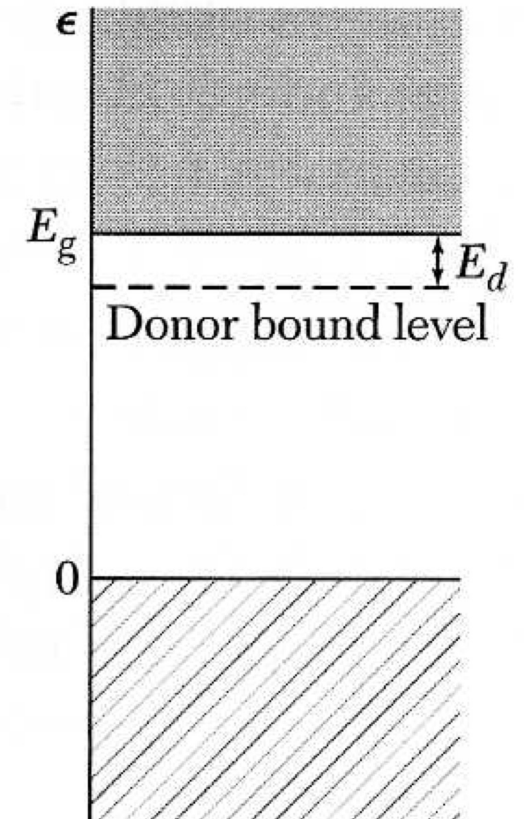
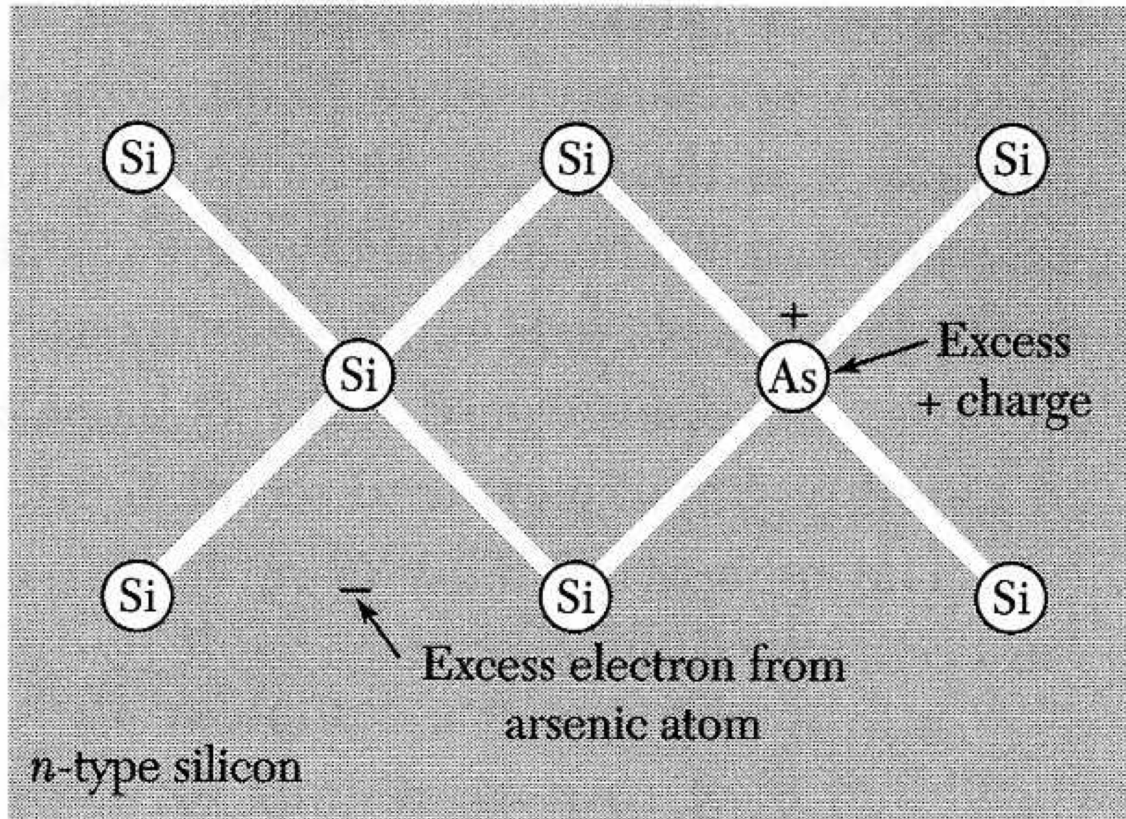


$\text{Si}^{4+}$

$\text{B}^{3+}$

From Kittel

# Electron - doping

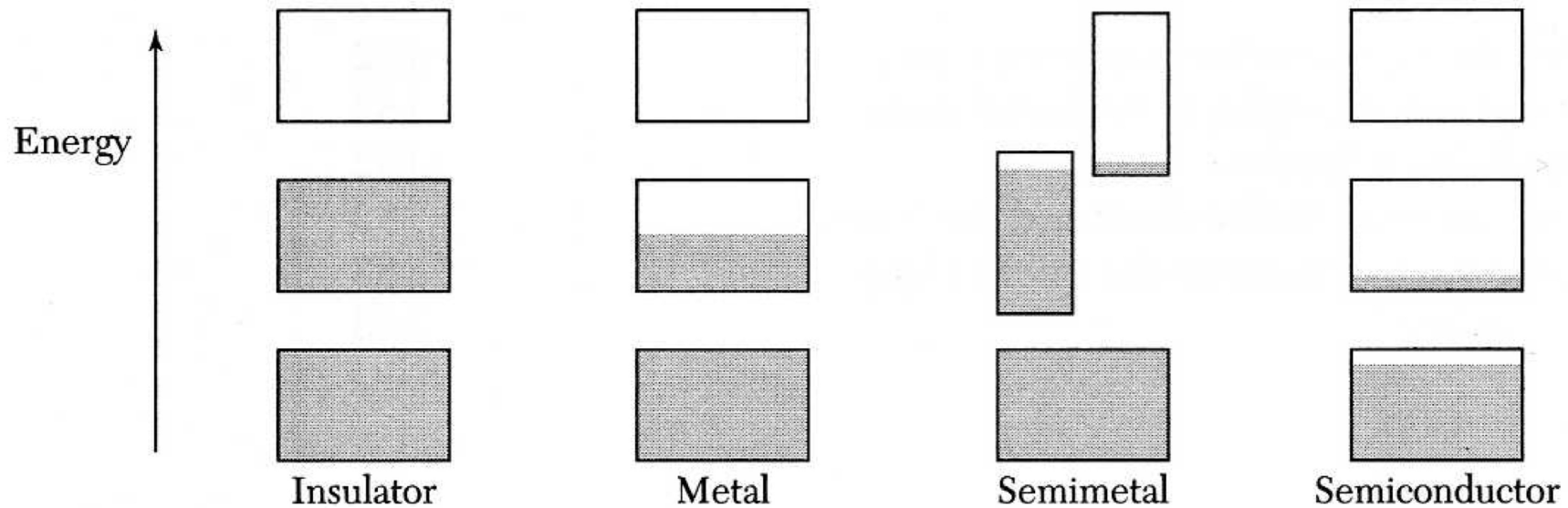


$\text{Si}^{4+}$

$\text{As}^{5+}$

# Concluding quiz

Does a semiconductor have a Fermi surface? (yes/no)



Does a semimetal have a Fermi surface? (yes/no)

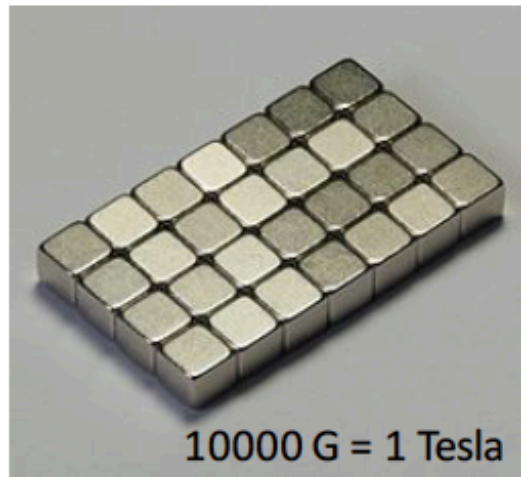
# Magnetic field

Human Brain



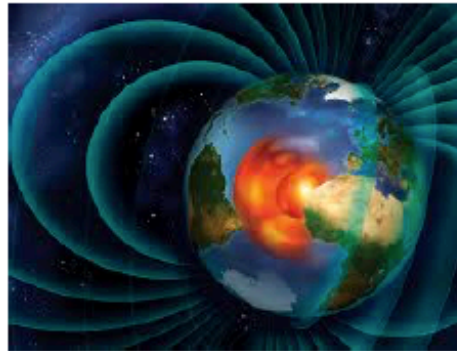
1 nG to 10 nG

Neodymium – iron – boron  
 $\text{Nd}_2\text{Fe}_{14}\text{B}$  Magnet



10000 G = 1 Tesla

Earth



0.25 - 0.65 Gauss

Static 45 –Tesla  
Hybrid magnet



Fridge Magnets



50 Gauss

100 Tesla  
Pulsed magnet

