Answers to Practice Test Questions 5A
Band Theory

1.

(a) The valence band is the highest energy band containing electrons.

(b) The conduction band is the lowest energy band which can accept electrons.

(c) An insulator is a material in which the energy gap between the valence and conduction bands is large enough that an electron cannot readily be excited from the valence band into the conduction band.

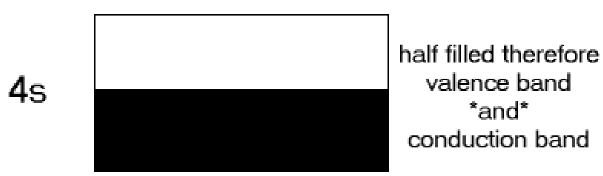
(d) An extrinsic semiconductor is a semiconductor which has been prepared by doping an element with another element in order to reduce the energy gap between the valence and conduction bands (due to the presence of additional bands from the dopant).

(e) An n-type semiconductor is an extrinsic semiconductor which has been prepared by doping an element with another element that has more valence electrons than it. The dopant introduces a donor band which is higher in energy than the original valence band, and those electrons can be excited into the conduction band, allowing for conduction of electricity and heat.

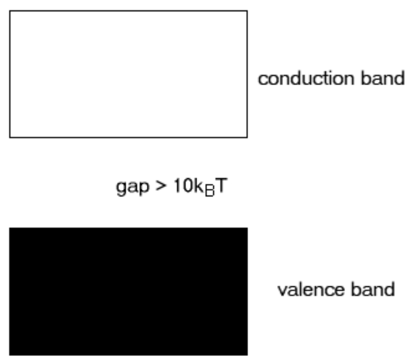
e.g. Si doped with P

2.

(a) band structure of potassium:



(b) band structure of silicon:



These diagrams show the valence band and conduction band for each element.
Core bands are not shown.

(c) Silicon is an insulator.

Potassium is definitely *not* an insulator! It is an excellent conductor as evidenced by the valence band and conduction band being the same band (allowing electrons to move readily from the valence band to conduction band).

Therefore, silicon must be the insulator. It has an energy gap between the valence band and conduction band that must be large enough ($>10k_B \cdot T$) to make it an insulator.

3.

(a) n-type

(b) Phosphorus has one more valence electron than silicon.

As a result, it provides a donor band (containing electrons) close in energy to the conduction band of the silicon.

Electrons in the donor band require less energy to be excited into the conduction band of silicon (compared to the electrons in the valence band of silicon).

The electrons excited into the conduction band can conduct electricity.

4. Insulators and semiconductors are characterized by having one band that is completely filled, i.e whose top coincides with the Fermi level, a gap, and then another band. The completely filled band is the valence band. The (mostly) empty band is the conduction band.

In insulators, the band gap is large so that electrons are unable to access the conduction band. Accordingly, the valence band remains completely filled and the conduction band empty at normal temperatures. In the ground state of a solid, every electron with a positive momentum is matched by an electron with an equal and opposite momentum, so that on average, there is no electron flow. In order for a material to conduct electricity, an electric field must shift the momentum distribution so that there is an excess of electrons with a positive momentum. This requires some electrons to access energies above the Fermi level. In an insulator, there are no states with energies sufficiently close to the filled valence band for this to happen.

Semiconductors have smaller band gaps than insulators, so at a sufficiently high temperature there are always some electrons that are able to go from the valence to the conduction band. When an electric field is applied, both the holes in the valence band and the electrons in the conduction band can move, leading to a modest current.

5.

(a) p-type

(b) Gallium has one less valence electron than germanium.

As a result, it provides an acceptor band (with space for electrons) close in energy to the valence band of the germanium.

Electrons in the valence band of germanium require less energy to be excited into the acceptor band from the gallium (compared to being excited into the conduction band of the germanium).

The “holes” left as electrons are excited out of the valence band of germanium can conduct electricity (as electrons move into the “holes”).

(c) The band gap is reported in kJ/mol, but it only requires one photon to excite one electron across the band gap. That photon can carry more energy than the band gap, but cannot carry less energy than the band gap. So, begin by calculating the energy of the lowest-energy photon that can excite a single electron across the band gap then calculate the wavelength for light with that energy.

Step 1: Convert the energy of the band gap from kJ/mol into J/photon.

$$E_{photon} = 62.7\ \frac{kJ}{mol} \times \frac{1000\ J}{1\ kJ} \times \frac{1\ mol}{6.022141 \times 10^{23} photons} = 1.04 \times 10^{-19}\ \frac{J}{photon}$$

Step 2: Calculate the wavelength of light corresponding to the energy of the band gap.

$$E_{photon} = h\nu \qquad \textit{and} \qquad c = \nu\lambda$$

$$E_{photon} = \frac{hc}{\lambda}$$

$$\lambda = \frac{hc}{E_{photon}} = \frac{\left(6.626070 \times 10^{-34}\ \frac{J}{Hz}\right)\left(2.997925 \times 10^{8}\ \frac{m}{s}\right)}{1.04 \times 10^{-19}\ J} \times \frac{1\ Hz}{1\ \frac{1}{s}} = 1.91 \times 10^{-6}\ m$$

$$\lambda = 1.91 \times 10^{-6}\ m \times \frac{10^{6}\ \mu m}{1\ m} = 1.91\ \mu m$$

Step 3: Check your work

Does your answer seem reasonable? Are sig. fig. correct?

6. When a semiconductor absorbs energy, an electron is excited from the valence band into the conduction band.

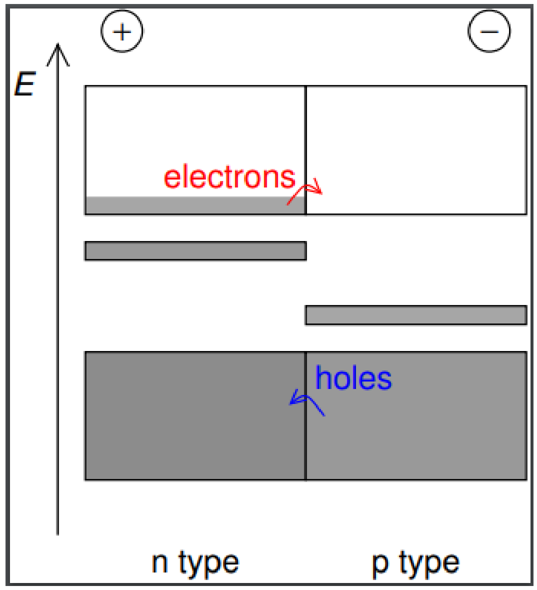
When the electron falls back down into the valence band, energy is released – in this case, as a photon of light.

The energy difference between the conduction band and valence band is equal to the energy of the photon which is released.

Larger particles contain more atoms. Thus, they have more atomic orbitals combining to form the bands and there are more states within each band. As such, the gaps between energy levels (both within and between bands) are smaller.

Violet light is higher in energy than red light. (E = hν where ν is greater for violet light) Thus, it makes sense that the larger particles (which have smaller gaps between bands) will emit red light while the smaller particles (which have larger gaps between bands) will emit violet light.

7.



In a diode that has not been connected to a circuit, electrons diffuse (since this maximizes the entropy!) from the partially filled conduction band of the n-type semiconductor, to the empty conduction band of the p-type semiconductor. Holes also diffuse from the p-type valence band to the n-type valence band. Both of these effects result in the n-type material becoming positively charged, while the p-type material becomes negatively charged. An equilibrium is rapidly established in which electrons attracted back to the positive n-type material from the p side balance the diffusion of electrons from the n side to the p side.

If we connect the negative pole of a battery to the n side and the positive pole to the p side, electrons can flow easily because the excess electrons on the p side can exit the material and be replenished from the n side. However, if we connect the negative pole to the p side, we are trying to push electrons into a negatively charged material, which results in significant resistance to current flow. A current can be established only if the applied voltage exceeds the potential difference between the n and p side due to the charge separation.