Chapter 11

1.

$$\log R + \frac{K}{\log R} = A + \frac{B}{T}$$

This can be rearranged to find

$$(\log R)^2 - \left(A + \frac{B}{T}\right)(\log R) + K = 0$$

This is a quadratic equation that can be solved numerically at any given temperature.

a) $T = 77$ K: $\log R = 2.372$ so $R = 236\ \Omega$

b) $T = 20$ K: $\log R = 2.786$ so $R = 610\ \Omega$

c) $T = 1$ K: $\log R = 7.7389$ so $R = 5.48 \times 10^7\ \Omega$

2.

$$\log R + \frac{K}{\log R} = A + \frac{B}{T}$$

Inserting each of the R and T values, we have three equations in three unknowns (A, B, K), which can be solved to yield $A = 2.09$, $B = 1.96$, $K = 1.10$.

3. Positive charges drift to the right, so the right side of the strip is at a higher potential and the voltmeter reads positive.

* 4. a) Starting from Equation (11.6) and with $A = yz$, we have

$$n = \frac{IB}{eV_H z} = \frac{(0.10\ \text{A})(0.036\ \text{T})}{(1.602 \times 10^{-19}\ \text{C})(8.4 \times 10^{-3}\ \text{V})(1.5 \times 10^{-4}\ \text{m})} = 1.78 \times 10^{22}\ \text{m}^{-3}$$

b) Graphing B vs. V_H we find a slope of approximately 4.56 T/V. Algebraically, we see that $B = \frac{nez}{I} V_H$. Thus the slope, m is equal to $\frac{nez}{I}$. So

$$n = \frac{mI}{ez} = \frac{(4.56\ \text{T/V})(0.10\ \text{A})}{(1.602 \times 10^{-19}\ \text{C})(1.5 \times 10^{-4}\ \text{m})} = 1.90 \times 10^{22}\ \text{m}^{-3}$$

5. $E = V/L = Q\, dT/dx$ so

$$Q = \frac{V}{L\frac{dT}{dx}} = \frac{12.6 \times 10^{-6}\ \text{V}}{(0.10\ \text{m})\left(\frac{10\ \text{K}}{0.1\ \text{m}}\right)} = 1.26 \times 10^{-6}\ \text{V/K}$$

6. From the table 2.43 mV corresponds to 47.2°C.

7. Over most of the table 0.05 mV corresponds to a temperature change of 1°C. Therefore for 0.01°C there corresponds a voltage difference of (0.01) (0.05 mV) $= 5 \times 10^{-7}$ V.

* 8. a) Al is in Group III; Ge is in Group IV; so relative to Ge, it is p-type.

b) Se has two more outer electrons than Si, so it is n-type. Se is in Group VI; Ge is in Group IV.

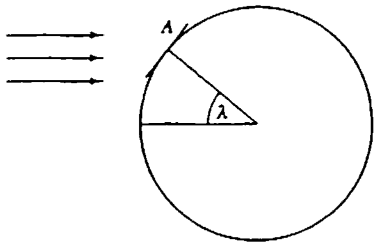
9. The relation between energy and photon wavelength is $E = \dfrac{hc}{\lambda}$. The photon must provide enough energy to excite the electron across the gap, so $\lambda = \dfrac{hc}{\Delta E}$.

a) $\lambda = \dfrac{1240\,\text{eV}\cdot\text{nm}}{0.67\,\text{eV}} = 1850\,\text{nm}$

b) $\lambda = \dfrac{1240\,\text{eV}\cdot\text{nm}}{1.10\,\text{eV}} = 1130\,\text{nm}$

10. The relation between energy and photon wavelength is $E = \dfrac{hc}{\lambda}$. A photon with wavelength 574 nm corresponds to $E = \dfrac{1240\,\text{eV}\cdot\text{nm}}{574\,\text{nm}} = 2.16\,\text{eV}$

11. The angle between the solar rays and a vector normal to the surface A is λ. Therefore $\Phi = \Phi_0 \cos\lambda$.



a) On the equinox $\lambda = 33°$ so $\Phi = \Phi_0 \cos(33°) = .839\Phi_0$

On the winter solstice $\lambda = 33° + 23° = 56°$ and $\Phi = \Phi_0 \cos(56°) = .559\Phi_0$

On the summer solstice $\lambda = 33° - 23° = 10°$ and $\Phi = \Phi_0 \cos(10°) = .985\Phi_0$

b) On the equinox $\lambda = 50°$ so $\Phi = \Phi_0 \cos(50°) = .643\Phi_0$

On the winter solstice $\lambda = 50° + 23° = 73°$ and $\Phi = \Phi_0 \cos(73°) = .292\Phi_0$

On the summer solstice $\lambda = 50° - 23° = 27°$ and $\Phi = \Phi_0 \cos(27°) = .891\Phi_0$

c) On the equinox $\lambda = 60°$ so $\Phi = \Phi_0 \cos(60°) = .500\Phi_0$

On the winter solstice $\lambda = 60° + 23° = 83°$ and $\Phi = \Phi_0 \cos(83°) = .122\Phi_0$

On the summer solstice $\lambda = 60° - 23° = 37°$ and $\Phi = \Phi_0 \cos(37°) = .799\Phi_0$

These results indicate why there is generally a larger temperature gradient (as a function of latitude) in winter than summer.

12. We require $10^9\ \text{W} = 0.3\left(200\,\text{W/m}^2\right) A$, so rearranging

$$A = \frac{10^9\ \text{W}}{0.3\left(200\ \text{W/m}^2\right)} = 1.67\times 10^7\ \text{m}^2$$

which corresponds to a square array 4.1 km on a side.

* 13. In general $I = I_0\left(\exp(eV/kT) - 1\right)$ and in Example 11.4

$$I_0 = \frac{I}{\exp(eV/kT) - 1} \approx 18.16\,\mu\text{A}$$

a)

$$I = \left(18.16\times 10^{-6}\text{A}\right)\left(\exp\left(\frac{0.250\ \text{eV}}{(8.617\times 10^{-5}\ \text{eV/K})\,(250\ \text{K})}\right) - 1\right) = 1.99\,\text{A}$$

b)

$$I = \left(18.16\ \times 10^{-6}\text{A}\right)\left(\exp\left(\frac{0.250\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})\,(300\text{ K})}\right)-1\right) = 0.288\,\text{A} = 288\,\text{mA}$$

c)

$$I = \left(18.16\ \times 10^{-6}\text{A}\right)\left(\exp\left(\frac{0.250\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})\,(500\text{ K})}\right)-1\right) = 0.006\,\text{A} = 6.00\,\text{mA}$$

* 14. Since the tube is single-walled, we can find the surface area density, σ in SI units. Each atom has mass 12 u, with $\text{u} = 1.6605\times10^{-27}$ kg.

$$\sigma = \left(2.3\times10^{19}\,\text{atoms/m}^2\right)(12\,\text{u})\left(1.6605\times10^{-27}\,\text{kg/u}\right) = 4.58\times10^{-7}\,\text{kg/m}^2$$

a) To determine the density of the material, we need the mass per unit volume. The mass will equal the mass density, σ from above, times the area A of the cylindrical wall. If the tube's length is L with radius R, then $m = 2\pi RL\sigma$. Therefore the density will be

$$\rho = \frac{m}{V} = \frac{2\pi RL\sigma}{\pi R^2 L} = \frac{2\sigma}{R} = \frac{2\left(4.58\times10^{-7}\,\text{kg/m}^2\right)}{0.7\times10^{-9}\,\text{m}} = 1300\,\text{kg/m}^3$$

b) The material is less dense than steel and has a greater tensile strength.

15. We know the density of the single-walled nanotube from the previous problem. Consider a tube that is 1 nanometer long. The tube will contain one buckyball. The total mass will be the mass of the tube plus the mass of the buckyball which is

$$m = \rho V + (60)(12\,\text{u})\left(1.6605\times10^{-27}\,\text{kg/u}\right) = \rho\left(\pi R^2 L\right) + 1.20\times10^{-24}\,\text{kg}$$

We find the ρV term equal to 2.0×10^{-24} kg, so the total mass equals 3.2×10^{-24} kg. Therefore the density of the nanotube peopod is

$$\rho = \frac{m}{V} = \frac{3.2\times10^{-24}\,\text{kg}}{\pi R^2 L} = \frac{3.2\times10^{-24}\,\text{kg}}{\pi\left(0.7\times10^{-9}\,\text{m}\right)^2\left(1\times10^{-9}\,\text{m}\right)} = 2080\,\text{kg/m}^3$$

16. a) Using $E = E_g$ for the conduction band we have $E - E_F = E_g - E_g/2 = E_g/2$. Then

$$\exp\left[(E - E_F)/kT\right] = \exp\left[E_g/2kT\right]$$

With $E_g \approx 1$ eV for a semiconductor (and larger for an insulator), and $kT \approx \frac{1}{40}$ eV at room temperature, we can see that $E_g \gg 2kT$ and the exponential term will be much greater than 1, so we can neglect the +1 term in the Fermi-Dirac factor. This leaves

$$F_{FD} \approx \frac{1}{\exp\left[E_g/2kT\right]} = \exp\left[-E_g/2kT\right]$$

b)

$$F_{FD} \approx \exp\left[-E_g/2kT\right] = \exp\left(-\frac{6\text{ eV}}{2\,(8.617\times10^{-5}\text{ eV/K})\,(293\text{ K})}\right) = 2.5\times10^{-52}$$

c)

$$F_{FD} \approx \exp\left[-E_g/2kT\right] = \exp\left(-\frac{1.1 \text{ eV}}{2\left(8.617 \times 10^{-5} \text{ eV/K}\right)\left(293 \text{ K}\right)}\right) = 3.5 \times 10^{-10}$$

d) For one mole of silicon there are 6×10^{23} atoms, so there are still many conduction electrons available.

* 17. a) Replacing ϵ_0 with $\kappa\epsilon_0$ we have for the new Bohr radius

$$a_0' = \frac{4\pi\epsilon_0\kappa\hbar^2}{me^2} = 11.7a_0 = 11.7\left(5.29 \times 10^{-2} \text{ nm}\right) = 0.619 \text{ nm}$$

b) This value is about 2.6 times the lattice spacing. This is consistent with the fact that the electron is very weakly bound, and hence the doped silicon should have a higher electrical conductivity than pure silicon.

18. From Bohr theory

$$E_0 = \frac{me^4}{2\hbar^2\left(4\pi\epsilon_0^2\right)^2}$$

Replacing ϵ_0 with $\kappa\epsilon_0$ we have a new Rydberg energy

$$E_0' = \frac{me^4}{2\hbar^2\left(4\pi\epsilon_0^2\right)^2\kappa^2} = \frac{E_0}{\kappa^2} = \frac{13.6 \text{ eV}}{(11.7)^2} = 0.099 \text{ eV}$$

This is more than a factor of ten less than the band gap for pure silicon, again consistent with the idea that the doped version has a higher electrical conductivity.

19. Answers will vary depending on algorithms used, but students should find that using a second-order method results in some improvement.

* 20. a) $I = I_0\left(\exp\left(eV/kT\right) - 1\right)$. To find the value of V for the diode, use the loop rule: $V + IR = 6\,\text{V}$, so $V = 6 \text{ V} - IR$. We are given that $I_0 = 1.75\,\mu\text{A}$ and $I = 80$ mA with $T = 293$ K.

$$\frac{I}{I_0} = 45714 = \exp\left(eV/kT\right)$$

$$\ln 45714 = \frac{eV}{kT} = \frac{e\left(6 \text{ V} - IR\right)}{kT}$$

Solving for R we find

$$R = \frac{6 \text{ V} - \left(kT\ln 45714\right)/e}{I} = \frac{6 \text{ V} - \left(8.617 \times 10^{-5}\,\text{eV/K}\right)\left(293\,\text{K}\left(\ln 45714\right)\right)/e}{0.080\,\text{A}} = 71.6\,\Omega$$

b)

$$V_R = IR = \left(0.080 \text{ A}\right)\left(71.6 \ \Omega\right) = 5.73\,\text{V}$$

21. a) $8 = \exp\left(eV/kT\right) - 1$ so

$$V = \frac{kT\ln 9}{e} = \frac{\left(8.617 \times 10^{-5} \text{ eV/K}\right)\left(293 \text{ K}\right)\left(\ln 9\right)}{e} = 55.5 \text{ mV}$$

b) $-0.8 = \exp\left(eV/kT\right) - 1$ so

$$V = \frac{kT\ln 0.2}{e} = \frac{\left(8.617 \times 10^{-5} \text{ eV/K}\right)\left(293 \text{ K}\right)\left(\ln 0.2\right)}{e} = -40.6 \text{ mV}$$

22.

$$E_g = \frac{hc}{\lambda} = \frac{1240\ \text{eV}\cdot\text{nm}}{650\ \text{nm}} = 1.91\ \text{eV}$$

* 23.

$$E_g = \frac{hc}{\lambda} = \frac{1240\ \text{eV}\cdot\text{nm}}{460\ \text{nm}} = 2.70\ \text{eV}$$

24. a) The total area is $\left(12 \times 10^6\right)\left(1.3 \times 10^{-7}\ \text{m}\right)^2 = 2.03 \times 10^{-7}\ \text{m}^2$ so each side is the square root of this or 0.450 mm.

b) The area of each transistor is now $2.5 \times 10^{-15}\ \text{m}^2$, so the number is

$$N = \frac{2.03 \times 10^{-7}\ \text{m}^2}{2.5 \times 10^{-15}\ \text{m}^2} = 8.12 \times 10^7$$

or nearly a factor of 7 improvement.

25. From Problem 16 we have $F_{FD} \approx \exp\left[-E_g/2kT\right]$.

Si at $T = 0°\text{C}$: $$F_{FD} \approx \exp\left(-\frac{1.1\ \text{eV}}{2\,(8.617 \times 10^{-5}\ \text{eV/K})\,(273\ \text{K})}\right) = 7.02 \times 10^{-11}$$

Si at $T = 75°\text{C}$: $$F_{FD} \approx \exp\left(-\frac{1.1\ \text{eV}}{2\,(8.617 \times 10^{-5}\ \text{eV/K})\,(348\ \text{K})}\right) = 1.08 \times 10^{-8}$$

Ge at $T = 0°\text{C}$: $$F_{FD} \approx \exp\left(-\frac{0.67\ \text{eV}}{2\,(8.617 \times 10^{-5}\ \text{eV/K})\,(273\ \text{K})}\right) = 6.54 \times 10^{-7}$$

Ge at $T = 75°\text{C}$: $$F_{FD} \approx \exp\left(-\frac{0.67\ \text{eV}}{2\,(8.617 \times 10^{-5}\ \text{eV/K})\,(348\ \text{K})}\right) = 1.41 \times 10^{-5}$$

The Fermi-Dirac factor is orders of magnitude higher in germanium, making the conduction electron density too high. The result is a reverse-bias current that is too large. See Physics Today December 1997 p. 38.

26. a) Energy is power multiplied by time:

$$E = Pt = (0.15)\,(200\ \text{W})\,\left(3.156 \times 10^7\ \text{s}\right) = 9.47 \times 10^8\ \text{J}$$

b) Converting we find 2.8×10^{12} kW·h $= 1.01 \times 10^{19}$ J. Then the area is

$$\frac{1.01 \times 10^{19}\ \text{J}}{9.47 \times 10^8\ \text{J/m}^2} = 1.06 \times 10^{10}\,\text{m}^2$$

c) Using 2.5 times the area in (b) the fraction of the U.S. covered is

$$\frac{2.5\left(1.06 \times 10^{10}\,\text{m}^2\right)}{9.6 \times 10^{12}\ \text{m}^2} = 0.0028$$

or one-fourth of one percent. See American Scientist July-August 1993, p. 368.

27. From the diode equation the current is $I = I_0 \exp(eV/kT) - 1$. Then the ratio is

$$\frac{I_f}{I_r} = \frac{I_0 \exp(eV_f/kT) - 1}{I_0 \exp(eV_r/kT) - 1}$$

a)

At $T = 77$ K: $$\frac{I_f}{I_r} = \frac{\exp\left(\frac{1.50\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})(77\text{ K})}\right) - 1}{\exp\left(\frac{-1.50\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})(77\text{ K})}\right) - 1} = -1.5 \times 10^{98}$$

At $T = 273$ K: $$\frac{I_f}{I_r} = \frac{\exp\left(\frac{1.50\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})(273\text{ K})}\right) - 1}{\exp\left(\frac{-1.50\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})(273\text{ K})}\right) - 1} = -4.9 \times 10^{27}$$

At $T = 340$ K: $$\frac{I_f}{I_r} = \frac{\exp\left(\frac{1.50\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})(340\text{ K})}\right) - 1}{\exp\left(\frac{-1.50\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})(340\text{ K})}\right) - 1} = -1.7 \times 10^{22}$$

At $T = 500$ K: $$\frac{I_f}{I_r} = \frac{\exp\left(\frac{1.50\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})(500\text{ K})}\right) - 1}{\exp\left(\frac{-1.50\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})(500\text{ K})}\right) - 1} = -1.3 \times 10^{15}$$

b) The ratio changes fairly significantly as a function of temperature. which is something diode designers must keep in mind.

28. a) An electron can be produced if the 1.1 eV band gap can be overcome. If we divide the total energy available by the band gap energy, the maximum number of electrons that can be produced is

$$N = \frac{1.04 \times 10^6\text{ eV}}{1.1\text{ eV}} = 9.45 \times 10^5$$

b) If the silicon is cooled well below room temperature, very few electrons will be in the conduction band. At room temperature, however, enough electrons are in the conduction band that additional current will be measured, tending to mask the gamma-ray signal.

29. From the diode equation the current is $I = I_0 \exp(eV/kT) - 1$. Then the ratio is

$$\frac{I_f}{I_r} = \frac{I_0 \exp(eV_f/kT) - 1}{I_0 \exp(eV_r/kT) - 1} = \frac{\exp(eV_f/kT) - 1}{\exp(eV_r/kT) - 1}$$

Substititing the values given. we find

$$\frac{I_f}{I_r} = \frac{\exp\left(\frac{0.1\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})(293\text{ K})}\right) - 1}{\exp\left(\frac{-0.1\text{ eV}}{(8.617\times10^{-5}\text{ eV/K})(293\text{ K})}\right) - 1} = -52.5$$

So the ratio of the currents in forward and reverse is 52.5.

30. Young's Modulus relates the elongation of an object due to an applied force. The formula is $Y = \frac{F}{A}\left(\frac{L}{\Delta L}\right)$. Rearranging this formula to solve for F and subtituting. we find

$$F = YA\left(\frac{\Delta L}{L}\right) = 1050 \times 10^9\,\text{Pa}\left(\frac{\pi(1.6 \times 10^{-9}\text{ m})^2}{4}\right)(0.01) = 2.1 \times 10^{-8}\,\text{N}$$

* 31. The number of bits stored is $(4.7 \times 10^9)(8) = 3.76 \times 10^{10}$ bits. To find the area we use $A = \pi\left(r_2^2 - r_1^2\right) = \pi\left(0.058^2 - 0.023^2\right) = 8.91 \times 10^{-3}\,\mathrm{m}^2$. The number of bits stored per square meter is then

$$\frac{3.76 \times 10^{10}\,\text{bits}}{8.91 \times 10^{-3}\,\mathrm{m}^2} = 4.2 \times 10^{12}\,\text{bits/m}^2 .$$