PHYSICS 2800 – 2^{nd} TERM
Introduction to Materials Science

<u>Assignment 2</u> – <u>with Outline Answers</u>

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The magnitude $|e|$ of the electronic charge is 1.6×10^{-19} C.

1. (a) Calculate the electrical conductivity of a 5.1-mm diameter cylindrical Si specimen that is 51 mm long, given that a current of 0.1 A flows in the length direction and a voltage of 12.5 V is measured between two probes that are separated by 38 mm.

(b) Deduce the resistance of the sample over its full 51 mm length.

(a) $\sigma = \ell/RA$ and $V = IR$, implying that $\sigma = \ell I/VA$

$$\therefore\ \sigma = \frac{38\times10^{-3}\times0.1}{12.5\times\frac{1}{4}\times\pi\times(5.1)^2\times10^{-6}} = 14.9\ (\Omega.\text{m})^{-1}$$

(b) Between the probes, $R_{\text{probes}} = V/I = 12.5/0.1 = 125\ \Omega$

But $R \propto \ell$, so $\dfrac{R}{125} = \dfrac{51}{38}$

$\therefore$ For the whole sample, $R = 168\ \Omega$

2. (a) Calculate the drift velocity of the electrons in Ge at room temperature when the magnitude of the electric field is 1000 V/m. The electron mobility is 0.38 m^2/V.s.

(b) Under these circumstances, how long does it take an electron to traverse a 25-mm length of the material?

(a) $v_d = \mu_e E$

But $\mu_e = 0.38\ \text{m}^2/\text{V.s}$ and $E = 1000$ V/m

$\therefore\ v_d = 0.38 \times 1000 = 380$ m/s

(b) If $\ell = 25$ mm, $t = \ell/v_d = \dfrac{25\times10^{-3}}{380} = 6.6 \times 10^{-5}$ s

3. At room temperature the electrical conductivity of PbS is 25 $(\Omega.\text{m})^{-1}$, whereas the electron and hole mobilities are 0.06 and 0.02 m^2/V.s, respectively. Calculate the intrinsic carrier concentration for PbS at room temperature.

σ = 25 $(\Omega.\text{m})^{-1}$, μ_e = 0.06 $\text{m}^2/\text{V.s}$, μ_h = 0.02 $\text{m}^2/\text{V.s}$

In the intrinsic region, $n = p = n_i$, so $\sigma = n_i |e| (\mu_e + \mu_h)$,

$$\therefore \quad n_i = \sigma/|e| (\mu_e + \mu_h) = \frac{25}{1.6\times10^{-19}\times(0.06+0.02)} = 1.95\times10^{21} \text{ m}^{-3}$$

4. The element Ge to which 10^{24} m^{-3} As atoms have been added is an extrinsic semiconductor at room temperature, and virtually all the As atoms may be thought of as being ionized (i.e., one charge carrier exists for each As atom). (a) Is this material n-type or p-type, and explain your reasons? (You may refer to the Periodic Table if needed). (b) Calculate the electrical conductivity of this material, assuming the electron and hole mobilities in Ge are 0.1 and 0.05 $\text{m}^2/\text{V.s}$, respectively.

(a) Ge doped with As.
Ge is in Group IVA (the same as Si), and As is in Group VA.
Therefore one electron is left over (as donor electron).
$\therefore$ The extrinsic behaviour is n-type

(b) In n-type material, we have $n >> p$, so $\sigma = n |e| \mu_e$ to a good approximation.
$\therefore$ $\sigma = 10^{24}\times 1.6\times10^{-19}\times 0.1 = 1.6\times10^{4}$ $(\Omega.\text{m})^{-1}$
Note that the hole mobility is not needed.

5. A Si p-n junction rectifier usually operates at room temperature. Qualitatively what would you expect to be the effects of increasing the operating temperature (a) slightly (e.g., to 350 K) and (b) substantially (e.g., to 550 K) on the effectiveness of the device as a rectifier? Explain why.

For the *rectifier*, we need the current I_F in forward bias to be large (for a given V_0), so large σ is good. We also need the difference between n- and p-type materials for the device to work. σ depends on the charge carrier concentration (n or p) and the corresponding mobilities.

As T is increased slightly above room temp in the extrinsic region, n and p are roughly constant (see the notes), but the mobilities tend to decrease. $\therefore$ The device effectiveness is reduced slightly for moderate increase in T.

At much higher T (e.g. above about 500 K) the behaviour of the n and p materials both become intrinsic (i.e., there is essentially no difference between them). The rectifying property is wiped out.

6. At an initial temperature of 35 C, a cylindrical rod of tungsten has a 15.025 mm diameter and a plate of steel has a circular hole of 15.000 mm diameter drilled through it. To what final temperature must they both be heated for the rod to just fit into the hole? Assume that the coefficients of linear expansion are 4.5×10^{-6} C^{-1} and 12.0×10^{-6} C^{-1}, respectively, for tungsten and steel.

The steel (and hence the size of the hole) expands more than the tungsten rod as T is increased. Therefore the rod will eventually fit when the two diameters are equal.
Suppose the increase in temperature needed is ΔT.
New diameter of rod $= 15.025 + 15.025\alpha_{\text{rod}}\Delta T$
New diameter of hole $= 15.000 + 15.000\alpha_{\text{steel}}\Delta T$
When these are the same, we have (by subtraction),

$$0.025 + (15.025\alpha_{\text{rod}} - 15.000\alpha_{\text{steel}})\,\Delta T = 0$$

$\therefore$ $\Delta T = 0.025 \div [(180 - 68) \times 10^{-6}] = 223$ C
$\therefore$ Final temperature $= 35 + 223 = 258$ C

7. The constant A in the formula $C = A\,T^3$ for the heat capacity is given by $12\pi^4 R/5\theta_D^{\,3}$ where R is the gas constant and θ_D is the Debye temperature (in K). Estimate the heat capacity (in J/mole-K) and the Debye temperature for Cu given that its specific heat at a temperature of 10 K is 0.78 J/kg-K. Assume that the value of R is 8.31 J/mole-K and the atomic weight of Cu is 63.6. [*Hint:* to convert between mole units and kg units, recall that the mass (expressed in grams) of one mole of an element is equal to the atomic weight.]

$C = A\,T^3$, and when $T = 10$ K we know specific heat = 0.78 J/kg-K.
$\therefore$ heat capacity $C = 0.78 \times (63.6 / 1000) = 0.050$ J/mol-K
So $A = 0.050 / 10^3 = 5.0 \times 10^{-5} = 12\,\pi^4\,R / 5(\theta_D)^3$
$\therefore$ $(\theta_D)^3 = 12\,\pi^4\,R / 5A = 38.9 \times 10^6$
So $\theta_D = 340$ K