ECSE-2210 Microelectronics Technology
Class Activity 4 – Solution

1) Write down the word definition of $g_c(E)$ and $g_v(E)$.

   $g_c(E)$ is density of states for electrons in the conduction band per unit volume per unit energy. $g_v(E)$ is the density of the states for the holes in the valence band per unit volume per unit energy.
   $g_c(E)$ and $g_v(E)$ give the distribution of states in the conduction and valence band.

2) Calculate the numerical value (in units of cm^{-3}) of the following integral (assume Si). This should not take more than 30 seconds

   The integration gives the total number of states in the conduction band.

$$\int_{E_{\mathrm{C-bottom}}}^{E_{\mathrm{C-top}}} g_c(E)\,\mathrm{d}E = 4\times 5\times 10^{22} \text{ states/cm}^3$$

   5×10^{22} / cm^3 = Total # of the Si atoms / cm^3
   There are 4 states per Si atom.
   So, the total number of states in 1 cm^3 of silicon is $4 \times 5 \times 10^{22}$ states/cm^3

3) If the Fermi function is as given below, calculate $f(E)$ at $E = E_F$ for $T > 0$

$$f(E) = 1 / [1 + \exp\left(\frac{0}{kT}\right)] = \frac{1}{1\ +\ 1} = 0.5$$

4) The following Fermi-Dirac (F-D) probability distribution function applies to electrons. What will be the F-D distribution function for holes?

   Probability of **NOT FINDING** electrons at a state at energy E will be $= 1 - f(E)$ if $f(E)$ corresponds to probability of finding electrons in a state at energy E. It is the same as saying that the probability of finding holes is $1 - f(E)$.

5) The probability that an electron will occupy a state at the energy E_C is the same as the probability that a hole will occupy a state at the energy E_V. What is the energy E_F of the Fermi-level? Show your work.

   $1 / [1 + \exp\left(\frac{E_C - E_F}{kT}\right)]$ = Probability that an electron will occupy a state at E_C

   $1 - 1/ [1 + \exp\left(\frac{E_V - E_F}{kT}\right)]$ = Probability that an electron will not occupy a state at E_V, i.e., a hole will occupy a state E_V

We have,

$$1/\left[1+\exp\left(\frac{E_C - E_F}{kT}\right)\right] = 1 - 1/\left[1+\exp\left(\frac{E_V - E_F}{kT}\right)\right]$$

$$= \exp\left(\frac{E_V - E_F}{kT}\right) / \left[1+\exp\left(\frac{E_V - E_F}{kT}\right)\right]$$

$$= 1/\left[1+\exp\left(\frac{E_F - E_V}{kT}\right)\right]$$

➔ $E_C - E_F = E_F - E_V$

➔ $E_F = \frac{E_C + E_V}{2}$ = at the middle of the band gap (see page 44 of text).

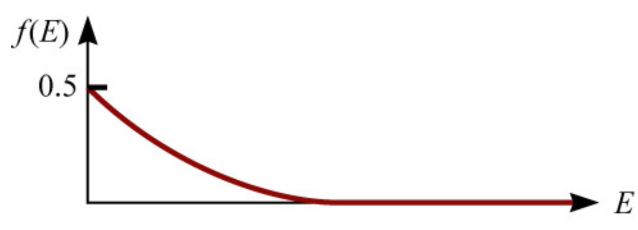
6) What is the Fermi-level? (Explain in your own words)

An energy below which all available states are filled with electrons at 0 K or a level where the electron occupation probability is 0.5 at $T > 0$K.

7) Assume that the energy E_F of the Fermi-level is $3kT$ below the conduction band edge, E_C. Show that the filled-state probability [given by $f(E)$] in the conduction band decays exponentially to zero with increasing energy. Plot $f(E)$ as a function of E, for $E > E_c$. ***Hint***: What is the relationship for $f(E)$ if $E > E_C$. Make a reasonable approximation since $E_C - E_F = 3kT$.]

$$f(E) = 1/\left[1+\exp\left(\frac{E - E_F}{kT}\right)\right] \approx^{(*)} 1/\left[\exp\left(\frac{E - E_F}{kT}\right)\right] = \exp\left(-\frac{E - E_F}{kT}\right) \approx e^{-3}$$

(*) neglecting 1 compared to $\exp\left(\frac{E - E_F}{kT}\right)$ since $E_C - E_F > 3kT$

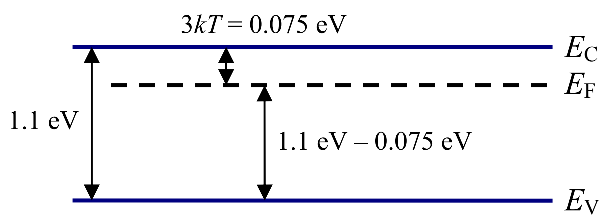


8) Consider Problem 7. Assume Si (E_g = 1.1 eV) and T = 300 K. Calculate the probability that an electron will occupy a state at E_C. Calculate the probability that an electron will occupy a

state at E_V. Also, calculate the probability that a state at E_V will be **free of electrons**. In this particular case, will the sample be n-type or p-type?

$f(E_C) = 1 / (1+ e^3) = 0.05$ (This is the probability of finding an electron at E_C).

$1 - f(E_V) = 1 - 1 / [1+\exp\left(\frac{E_V - E_F}{kT}\right)] \approx 1 - 1 = 0$ (close to 0)



Note: $E_V = E_F + 3kT - 1.1$ eV;
$kT = 0.025$ eV at 300 K.

9) Draw band diagrams for intrinsic, n-type and p-type semiconductors. Show the general position of the Fermi-level for each semiconductor, and mark E_C, E_V and E_i in the diagram.