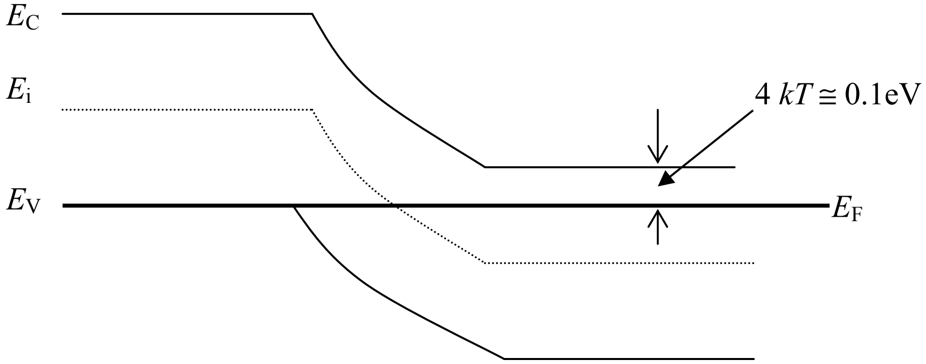
ECSE-2210 Microelectronics Technology
Class Activity 11 – Solution

1. A Si step junction maintained at room temperature is doped such that $E_F = E_V$ on the p-side and $E_F = E_C - 4kT$ on the n-side.
   a. Draw the equilibrium energy band diagram for this junction.



   b. Determine the built-in voltage (V_{bi}). (Read-off from the diagram above)

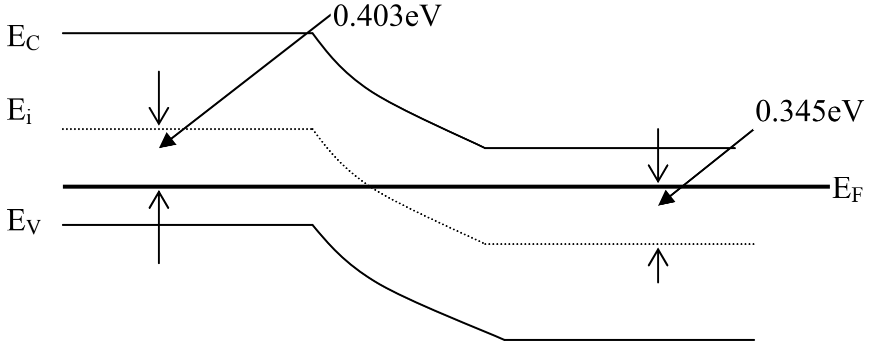
V_{bi} = $1/q\{(E_i - E_F)_{\text{p-side}} + (E_F - E_i)_{\text{n-side}}\}$ =
$1/q\{0.55\text{eV} + (0.55-0.1)\text{eV}\}$ = 1V

It is easier to remember this equation as: (1/q) {E_i(p-side) – E_i(n-side)} and obtaining the difference by looking at the band diagram.

2. An abrupt Si p-n junction has the doping concentrations as follows:
   P-side: $N_A = 1.5 \times 10^{17}\ \text{cm}^{-3}$, and $N_D = 5 \times 10^{16}\ \text{cm}^{-3}$.
   N-side: $N_A = 0$, and $N_D = 1 \times 10^{16}\ \text{cm}^{-3}$.
   Calculate the position of the Fermi levels at 300 K, draw the equilibrium band diagram and find the built-in voltage, V_{bi}, from the diagram. Also, calculate the built-in voltage, V_{bi}, from equation 5.10. in the textbook

$$V_{bi} = \frac{kT}{q}\ln(\frac{N_A N_D}{n_i^2})$$

$E_i - E_F$ (p-side) = $kT\ln(p/n_i)$ = 0.025 eV $\ln\{(1.5 \times 10^{17} - 5 \times 10^{16})/10^{10}\}$ = 0.403 eV
$E_F - E_i$ (n-side) = $kT\ln(n/n_i)$ = 0.025 eV $\ln(10^{16}/10^{10})$ = 0.345 eV
So, the built-in voltage is 0.748 V.



Note that N_A and N_D are meant to be **effective** N_A and N_D in $V_{bi} = \frac{kT}{q}\ln(\frac{N_A N_D}{n_i^2})$

i.e., $N_A^{eff} = (1.5 \text{ x } 10^{17} - 5 \text{ x } 10^{16}) = 10^{17}$ cm^{-3} and
$N_D^{eff} = (1 \times 10^{16} - 0) = 10^{16}$. Cm-3

$V_{bi} = 0.025$ eV $\ln\{10^{17} \times 10^{16}/10^{20}\} = 0.748$ V same as above.

3. Compare the contact potential V_{bi} of the Si device of Problem 2 with similarly doped GaAs device. GaAs has an n_i value of 1×10^6cm^{-3}. What trend do you notice?

   $V_{bi} = 0.025$ eV $\ln\{10^{17} \times 10^{16}/10^{12}\} = 1.208$V
   The larger the band gap, the larger the built-in voltage.

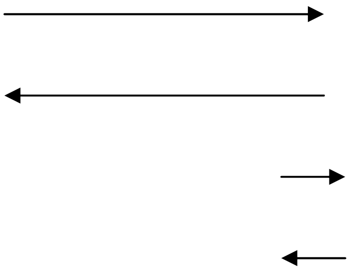
4. Can we measure this built-in voltage using a multi-meter? Explain.
   No. When we connect the multi-meter, you develop similar built-in voltages between the contact and the semiconductor. This one cancels out the built-in voltage we intend to measure. Built-in voltage determines the thermal equilibrium state in which no macroscopic currents are flowing, hence, no voltages can be measured with a multimeter.

5. Explain in your own words what is meant by the term "depletion layer or space charge layer"?
   When the p and n materials are brought together, the holes from the p-side and the electrons from the n-side diffuse to opposite sides. This leaves out electrically charged regions near the junction since the dopant atoms themselves cannot move. This region is called the depletion region since it is left by the free charge carriers (either holes or electrons) and contains mostly the immobile dopant atoms. It is also called space charge region because the electric charge in this region is non-zero.

6. In a p-n junction, what prevents the complete recombination of holes in the p-side with the electrons from the n-side? In other words, why can't the holes and electrons diffuse across the junction and make the concentration uniform throughout?
   The built in electric field because of the charged ions in the depletion region prevents the massive recombination of further electrons with the holes.

7. The p-n junction shown below is under thermal equilibrium. Qualitatively, mark the directions of hole currents (drift and diffusion) and electron currents (drift and diffusion). (Note: electron flux is opposite to electron current). Draw the length of the arrows to indicate the magnitude of the currents. Which will be larger? Hole currents or electron currents? No need to calculate anything.

p-type	n-type
$N_A=10^{17}$ cm^{-3}	$N_D=10^{15}$ cm^{-3}



$J_{p|diff}$ caused by 10^{17} cm^{-3} holes

$J_{p|drift}$ caused 10^{5} cm^{-3} holes in n-region to drift

$J_{n|diff}$ caused by only 10^{15} cm^{-3} electrons from n-region (100 times smaller)

$J_{n|drift}$ caused by only 10^{3} cm^{-3} electrons from p-region (100 times smaller)