$$\boxed{p_0 = n_i e^{(E_i - E_F)/kT} \rightarrow E_i - E_F = kT \ln(p_0/n_i)}$$

<u>ECE 3030.2 HW7</u>

<u>Prob. 1Use</u>

For the given n^+-p junction, calculate the capacitance.

C = Capacitance = $(\varepsilon_s/W)A$

$= A\,[qN_a\varepsilon_s/2(V_0 + V_R)]^{1/2}$ (Eq. 5-63, S&B)

Assume $E_F \sim E_c$ for the n^+ material.

$V_0 = 0.0259\ln(N_a/n_i) + 0.55$ (This is p-side Fermi level + ½ E_G for n-side Fermi level)

For $N_a = 10^{15}\text{cm}^{-3}$, V_0 = 0.84V = 0.287 + 0.55 = 0.837 eV

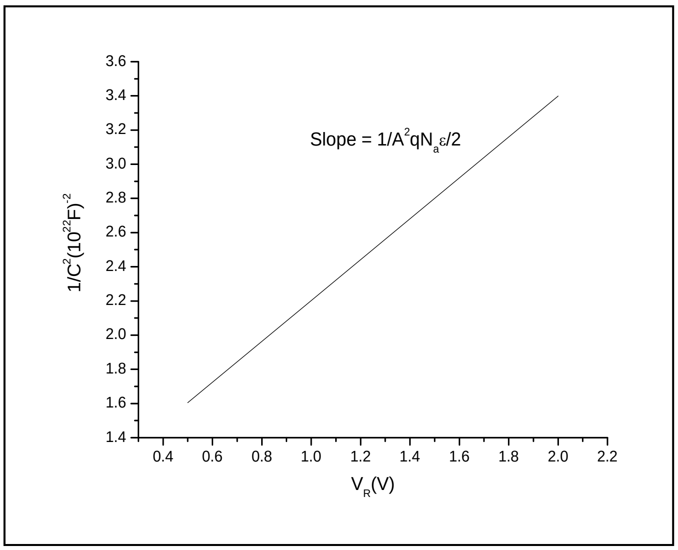
For $N_a = 10^{17}\text{cm}^{-3}$, V_0 = 0.96V = 0.41+ 0.55 = 0.0.957eV

For $N_a = 10^{15}\text{cm}^{-3}$,

$1/C^2 = 1/A^2[(V_0 + V_R)/qN_a\varepsilon_s/2] = (0.84 + V_R)/[(0.001)^2(1.6 \times 10^{-19})(10^{15})(11.8 \times 8.85 \times 10^{-14})/2]$

$= 1.197 \times 10^{22}(V^R + 0.84)$

which is linearly proportional to V_R with the slope being $1/[A^2qN_a\varepsilon_s/2]$, which in turn yields N_a. The plot of $1/C^2$ as a function of V_R is given below.



<u>Prob. 2</u>

For the p^+-n Si diode doped $N_d=3x10^{16}$ cm^{-3} on the n side, where D_p = 10 cm^2/s, τ_p = 0.1 μs and A= 10^{-4} cm^2, find C_j for -10 V and C_s for +0.6 V.

(Use Eq. 5-63 for p^+-n diode and $(V_0 - V) \sim V$)

$C_j = (A/2)[(2q\varepsilon/V_r)(N_d)]^{1/2} = (10^{-4}/2)[(2 \times 1.6 \times 10^{-19} \times 11.8 \times 8.85 \times 10^{-14} \times 3\text{x}10^{16})/10]^{1/2}$

= **1.56 pF**

Use $D_p\tau_p = L_p^{\,2} = (10\ \text{cm}^2/\text{s})(10^{-7}\ \text{s}) = 10^{-6}\ \text{cm}^2$ so $L_p = 10^{-3}$ cm

$I = qA[(D_p/L_p)p_n + (D_n/L_n)n_p]\,(e^{qV/kT} - 1) = qA[(D_p/L_p)p_n]\,(e^{qV/kT} - 1)$ since $p_n >> n_p$

See Example 5-4, p.199.

$(1.6 \times 10^{-19}\ \mathrm{A})(10^{-4}\ \mathrm{cm}^2)\ [10\ \mathrm{cm}^2/\mathrm{s}/10^{-3}\mathrm{cm}]\ (2.25\mathrm{x}10^{20}/(3\mathrm{x}10^{16}\ \mathrm{cm}^{-3}\ e^{0.6/0.0259}$

$= 3.6\mathrm{x}10^{-15\cdot}\ 1.15 \cdot 10^{10}\ \mathrm{A} = 4.14 \cdot 10^{-5} = 41.4\ \mu\mathrm{A}/3 = 13.8\ \mu\mathrm{A}$

Using τ and D to solve for L and I, $I = 13.8\ \mu$A at $V_f = 0.6$ V

$C_s = (qI\tau_p/kT) = (0.0259)^{-1} \times 13.8 \times 10^{-6} \times 10^{-7} =$ **53.3 pF**

<u>Prob.3</u>

Show $\mathcal{E}_0$ depends on doping on the lightly-doped side. Find V_r for a p^+-n junction. If $\mathcal{E}_0 = 400$ kV/cm for avalanche in a p^+-n Si junction with $N_d = 10^{16}$, what is V_{br}?

With bias, replace V_0 by $V_0 - V$. For a large reverse bias, $V_0 - V \sim V_r$

$$\mathcal{E}_0 = (-q/\varepsilon)(N_d x_{n0}) = -(q/\varepsilon)[(2\varepsilon V_r/q)(N_a N_d/N_a + N_d)]^{1/2} = -[(2q/\varepsilon)(V_r)(1/N_a + 1/N_d)^{-1}]^{1/2}$$

so, if N_a or N_d is large, the other one dominates.

For a p^+-n, $N_a >> N_d$ and

$$\mathcal{E}_0 = -[(2q/\varepsilon)(V_r N_d)]^{1/2},\ \text{or } V_r = \varepsilon E^2_0/2qN_d$$

For the numbers given,

$$V_r = (11.8 \times 8.85 \times 10^{-14})(1.6 \times 10^{11})/2 \times 1.6 \times 10^{-19} \times 10^{16} = \mathbf{52\ V}$$

which agrees with V_{br} vs. doping curve **S&B Figure 5-22.**

<u>Prob. 4</u>

Find V_{br} for a Si p-n junction with 4×10^{18}cm^{-3} doping on each side if Zener tunneling occurs at 10^6 V/cm.

$$\mathcal{E}_{\max} = (qN_d/\varepsilon)[(2\varepsilon(V_0 - V)/q)(N_a/N_d(N_a + N_d)]^{1/2}$$

$$= [(2q(V_0 - V)/\varepsilon)(N_a N_d/N_a + N_d)]^{1/2} = [(q(V_0 - V)/\varepsilon)N_d]^{1/2}$$

for $N_a = N_d$. Thus, letting $\mathcal{E}_{\max} = E_{br}$, and $V = -V_{br}$, we can solve for V_{br}:

$V_0 + V_{br} = (\varepsilon/qN_d)(E^2_{br}) = (11.8)(8.85 \times 10^{-14})10^{12}/(1.6 \times 10^{-19})(4 \times 10^{18}) = 1.63\ V$

$V_0 = (kT/q)\ln N_a N_d/n_i^2 = 0.0259 \ln [16 \times 10^{36}/2.25 \times 10^{20}] = 1.005\ V$

Thus $V_{br} = 1.63 - 1.005 =$ **0.625 *V***

Prob. 5

For the given p^{+}-n diode, explain whether avalanche breakdown or punchthrough breakdown occurs.

$V_{avalanche}$ = 13V from **S&B 5-22.**

$W = [(2\varepsilon_s(V_0 + V_{Br})/qN_d]^{1/2} = [(2(11.8)(8.85\text{x}10^{-14})(0.956 + 13)/1.6 \text{ x } 10^{-19} \text{ x } 10^{17}]^{1/2}$

= **$4.27 \text{ x } 10^{-5}$ cm**

which is less than the 1 µm width of the n - region.

Therefore, avalanche breakdown occurs before punch through.

Problem 6. 2. *Schottky barrier on n – S_i with $N_d = 10^{17} cm^{-3}$*

$\Phi_m = 4.8\text{eV}$, $\chi_{si} = 4.0\text{eV}$

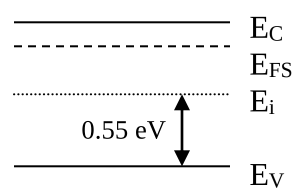
$n_0 = n_i e^{(E_F - E_i)/kT}$

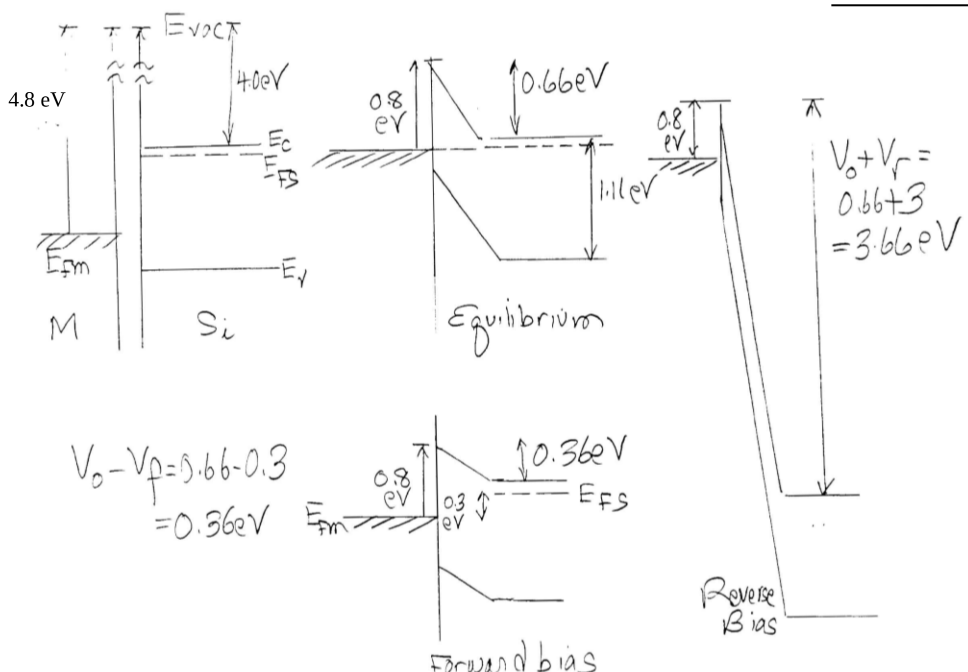
$E_F - E_i = kT\ln(n_0/n_i) = 0.0259\ln(10^{17}/1.5\text{x}10^{10}) = 0.0259(15.71) = 0.41\text{eV}$

$E_c - E_F = 0.55 - 0.41 = 0.14\text{eV}$

Therefore $q\Phi_s = q\chi + (E_c - E_F)$

$= 4.14$ eV and $qV_0 = 4.8 - 4.14 = 0.66\text{eV}$





(Depletion width should be larger.)

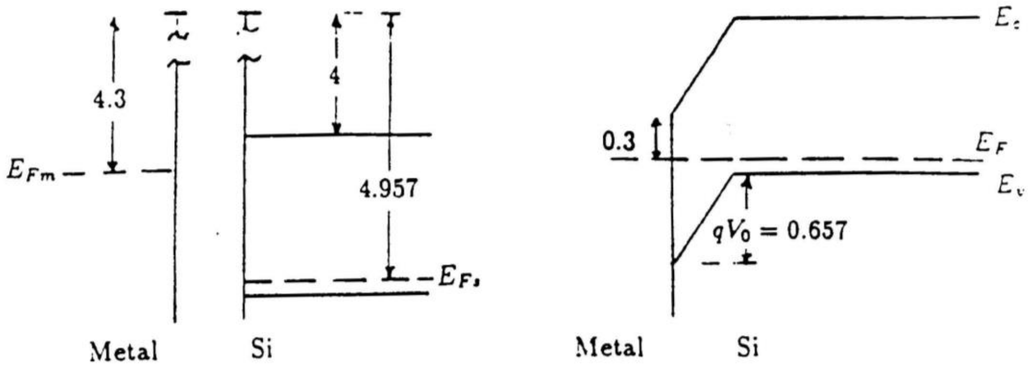
Prob. 7. *A Schottky barrier is formed between a metal having $\Phi_m = 4.3V$ and p-type Si (χ = 4V). The acceptor doping in the Si is $N_a = 10^{17} cm^{-3}$.*

(a) Draw the equilibrium band diagram, showing a numerical value for qV_0.

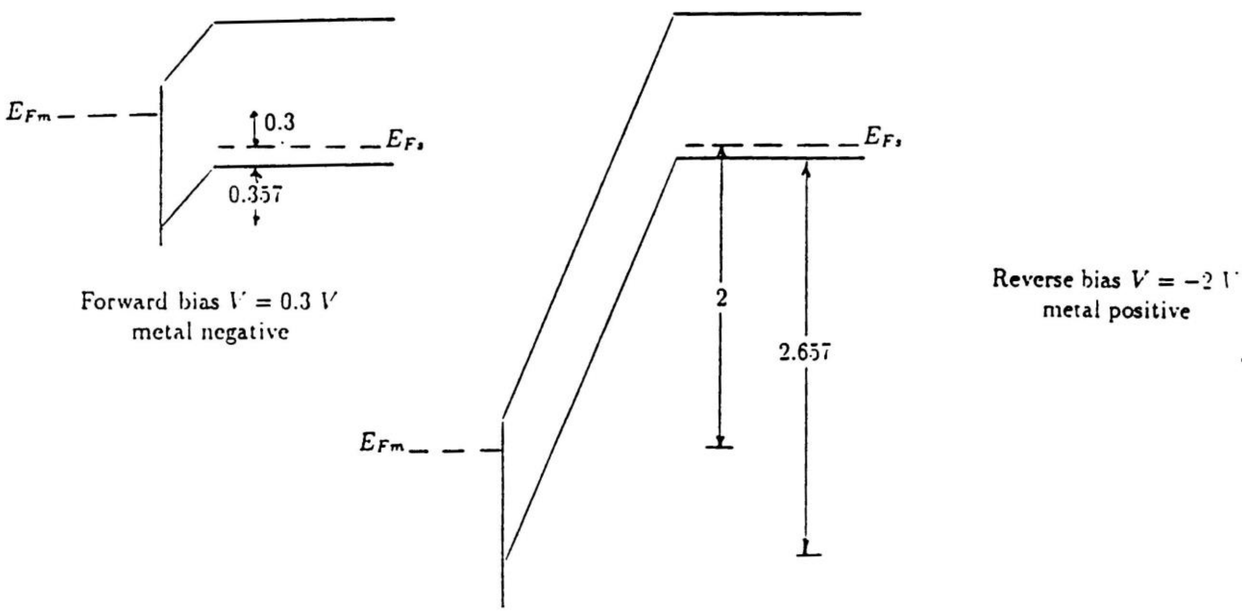
$E_i - E_F = kT\ln(p_0/n_i)$

$= 0.0259\ln(10^{17}/1.5 \times 10^{10}) = 0.407\text{eV}$

$\Phi_s = 4 + 0.55 + 0.407 = \mathbf{4.957\ eV}$



(b) *Draw the band diagram with* 0.3*V forward bias. Repeat for* 2*V reverse bias*.



<u>Prob. 8</u>

Find the area of a Si p^+*-n diode with* $V_{br} = 150$ *V and* $I_f = 1$ *mA at* 0.6 *V.*

Assume $\tau_p = 0.1\mu$ *s.*

For $V_{br} = 150V$, $N_d \simeq 3 \times 10^{15}\ \text{cm}^{-3}$ from **S&B** fig. 5-22.

Taking the hole mobility from **S&B** fig. 3-23, $\mu_p \sim 450\ cm^2$/V-s

$D_p/u_p = kT/q$

$D_p = 0.0259(450) = 11.7,$

$L_p = [11.7 \times 10^{-7}]^{1/2} = 1.08 \times 10^{-3}$

$p_n = 2.25 \times 10^{20}/3 \times 10^{15} = 7.5 \times 10^{4}$

$L_p^2 = D_p\tau_p$ so $D_p/L_p = L_p/\tau_p$ so

$I = qA(L_p/\tau_p)p_n e^{qV/kT}$ for $V >> kT/q$ and $N_a >> N_d$

$e^{qV/kT} = 1.15 \times 10^{10}$

$A = 10^{-3}[1.6 \times 10^{-19} \times 1.08 \times 10^{-3} \times 10^{7} \times 7.5 \times 10^{4} e^{0.6/0.0259}]^{-1}$

$= 6.7 \times 10^{-4}\ \text{cm}^2$

e.g., a circle of diameter 292 μm or a square $259\ \mu m$ on a side.
