Name Solutions

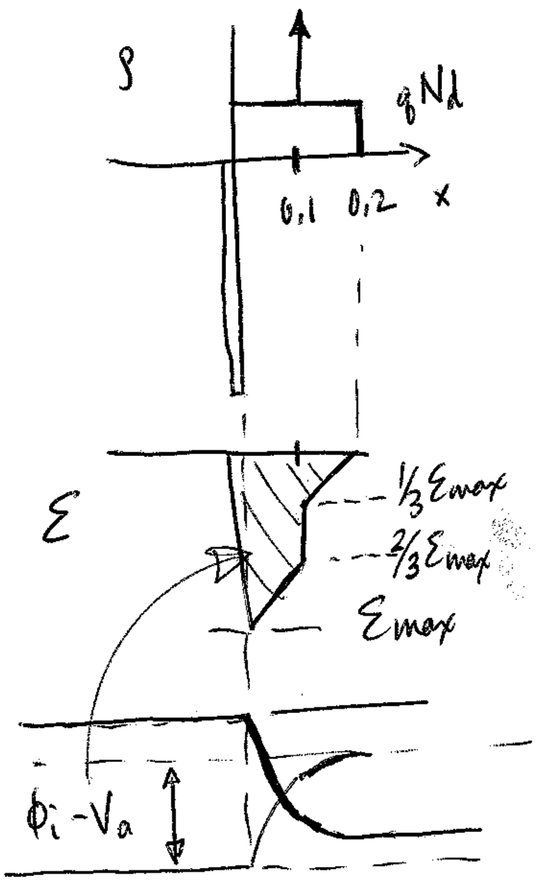
Mean = 55.1
Std. Dev. = 11.7

Exam #2 — EE 482
Fall 2002

The test is open book/open notes. Show all work. Be sure to state all assumptions made and **check** them when possible. The number of points per problem are indicated in parentheses. Total of 100 points in 4 problems on 4 pages

1. A silicon p-n junction is very heavily doped on the p-side ($E_f = E_v$) and has uniform doping of 10^{17}cm^{-3} on the n-side, except there is an additional narrow region of much heavier doping with dose of 10^{12}cm^{-2} located in the n region 0.1μm from the metallurgical junction. Note that the extra dose is given as doping per unit area rather than volume and treat as a delta-function.

   If the width of the depletion region on the n-side is 0.2μm, sketch the charge density, electric field and potential versus distance What is the applied bias? (22)



$$Q_d = q\left(10^{12} + 0.2\times10^{-4} * 10^{17}\right)\ \text{cm}^{-2}$$
$$= 4.8\times10^{-7}\,\text{C}$$

$$\mathcal{E}_{max} = -\frac{Q_d}{K_s\epsilon_0} = \frac{4.8\times10^{-7}\,\text{C}}{(11.7)(8.854\times10^{-14}\,\text{F/cm})} = 4.6\times10^{5}\,\frac{\text{V}}{\text{cm}}$$

$$\phi_i - V_a = \mathcal{E}_{max}\left[\frac{1+2/3}{2}\times0.1\mu\text{m} + \frac{1/3}{2}\times0.1\mu\text{m}\right]$$
$$= \mathcal{E}_{max}(0.1\mu\text{m}) = 4.6\,\text{V}$$

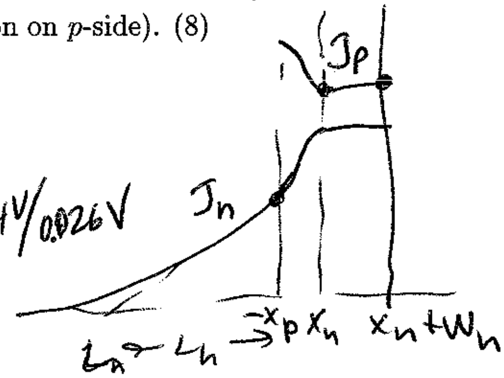
$$\phi_i = \frac{kT}{q}\ln\left(\frac{N_a N_d}{n_i^2}\right) \quad N_V$$
$$= 0.0259\,\text{V}\ \ln\left(\frac{(\ \times10^{19})(10^{17})}{2\times10^{20}\,\text{cm}}\right) = 0.94\,\text{V}$$

$$V_a = \phi_i - 4.6\,\text{V} = 0.94\,\text{V} = 4.6\,\text{V} = \underline{-3.76\,\text{V}}$$

2. Consider an abrupt silicon pn junction at 300K. The diode has a neutral p region with $W_p = 200\mu$m, doped with $N_a = 10^{16}\text{cm}^{-3}$ and a neutral n region with $W_n = 0.5\mu$m and $N_d = 10^{18}\text{cm}^{-3}$. $\tau_p = \tau_n = 10^{-6}$sec. $D_n = 9\,\text{cm}^2/\text{sec}$ and $D_p = 4\,\text{cm}^2/\text{sec}$ in the n-region and $D_n = 25\,\text{cm}^2/\text{sec}$ and $D_p = 9\,\text{cm}^2/\text{sec}$ in the p-region. The junction is operated in forward bias with $V_a = 0.4\,$V. Assume traps at midgap and $x_d' = x_d/10$.

$L_{np} = \sqrt{D_{np}\tau_n} = \sqrt{(25\,\text{cm}^2/\text{s})(10^{-6}\text{s})} = 5\times10^{-3}\,\text{cm} = 50\,\mu\text{m}$

(a) Calculate the electron current at $-x_p$ (edge of depletion region on p-side). (8)



$$J_n(-x_p) = q\frac{n_i^2}{N_a}\frac{D_{np}}{L_{np}}\left(\exp\left(\frac{qV_a}{kT}\right)-1\right)$$

$$= (1.6\times10^{-19}\,\text{C})\left(\frac{2\times10^{20}\,\text{cm}^{-6}}{10^{16}\,\text{cm}^{-3}}\right)\left(\frac{25\,\frac{\text{cm}^2}{\text{s}}}{5\times10^{-3}\,\text{cm}}\right)e^{0.4\text{V}/0.026\text{V}}$$

$$= 7.7\times10^{-5}\,\text{A}/\text{cm}^2$$

(b) Calculate the hole current at the contact to the n-region. (12)

$L_{pn} = \sqrt{(4\,\frac{\text{cm}^2}{\text{s}})(10^{-6}\text{s})} = 20\,\mu\text{m}$

$W_n \ll L_{pn}$

$$J_p(x_n+W_n) \cong J_p(x_n) = q\frac{n_i^2}{N_d}\frac{D_{pn}}{W_n}\left(\exp\left(\frac{qV_a}{kT}\right)-1\right)$$

$$= (1.6\times10^{-19}\,\text{C})\left(\frac{2\times10^{20}\,\text{cm}^{-6}}{10^{18}\,\text{cm}^{-3}}\right)\left(\frac{4\,\text{cm}^2/\text{s}}{0.5\times10^{-4}\,\text{cm}}\right)\exp\left(\frac{0.4}{0.026}\right)$$

$$= 1.23\times10^{-5}\,\text{A}/\text{cm}^2$$

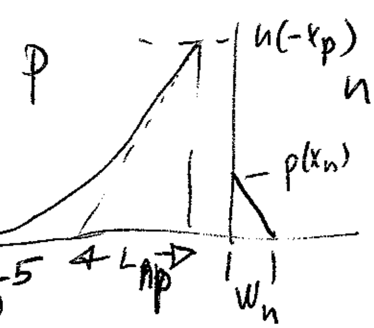
$$= \frac{D_{pn}}{D_{np}}\frac{L_{np}}{W_n}\frac{N_a}{N_d} * J_n(-x_p)$$

$$(4/25)(100)\left(\frac{1}{100}\right) * 7.7\times10^{-5}\,\text{A}/\text{cm}^2 = 1.23\times10^{-5}\,\frac{\text{A}}{\text{cm}^2}$$

(c) Calculate the ratio of stored minority charge in the n region to that in p-region. (6)

$$\frac{Q_{pn}}{Q_{np}} = \frac{q\,p(x_n)W_n/2}{q\,n(-x_p)\,L_{np}} = \frac{1}{100}\frac{(0.5\,\mu\text{m}/2)}{50\,\mu\text{m}}$$

$$= 1/20000 = 5\times10^{-5}$$



3 In a silicon ($\chi_s = 4\ 05$ V) MOS capacitor with an n-type substrate and a p+ polysilicon gate ($E_v - E_f = 0.1$eV), the substrate doping is uniform with $N_d = 10^{18}\text{cm}^{-3}$. The oxide thickness is 50 Å and there is a positive oxide charge of $Q_{ss} = 4 \times 10^{-8}$ C/cm^2 located at the oxide/semiconductor interface.

(a) Determine the state of the channel region (accumulation, flat-band, depletion, strong inversion, etc.) and sketch the charge density, electric field and energy band diagram for the system if the gate charge is $Q_g = -7 \times 10^{-7}$ C/cm^2 (12)

$\sum Q' = 0 = Q_g' + Q_{ss}' + Q_s'$;

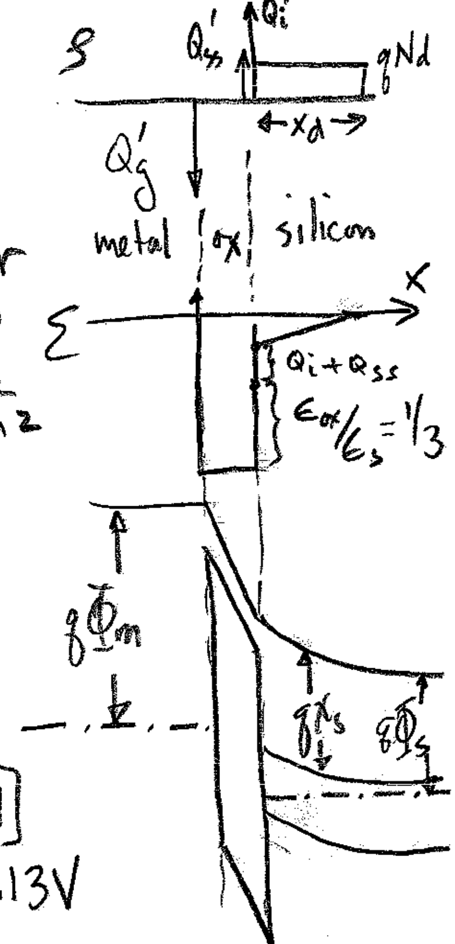
$Q_s' = -(Q_g' + Q_{ss}') = -(-7\times10^{-7}\frac{C}{cm^2} + 4\times10^{-8}\frac{C}{cm^2})$

$= 6.6\times10^{-7}\frac{C}{cm^2} > 0 \Rightarrow$ depletion (N_d^+) or inversion (h^+)

$Q'_{d,max} = Q_B' = \sqrt{2K_s\epsilon_0 q N_d |2\phi_F|} = 5.5\times10^{-7}\frac{C}{cm^2}$

$\phi_F = \frac{kT}{q}\ln\left(\frac{N_d}{n_i}\right) = 0.47$V

$Q_s' > Q_B' \Rightarrow$ inversion



(b) Determine the applied gate voltage. (12)

$V_{gb} = \Phi_{ms} + V_{ox} + V_s$ $\quad \Phi_{ms} = [\chi_s + \frac{E_g}{q} + 0.1] - [\chi_s + 0.09]$

$= 1.12 + 0.1 - 0.09 = 1.13$V

$\uparrow\ \frac{1}{q}(E_c - E_f)_{bulk} = \frac{kT}{q}\ln\left(\frac{N_c}{N_d}\right)$

$V_{ox} = \frac{Q_g'}{C_{ox}'} = \frac{-7\times10^{-7}\,C/cm^2}{6.9\times10^{-7}\,F/cm^2}$

$= -1.01$ V

$C_{ox}' = \frac{K_{ox}\epsilon_{ox}}{X_{ox}} = 6.9\times10^{-7}$ F/cm

$V_s = -2\phi_F$ in inversion

$V_{gb} = 1.13 - 1.01 - 2(0.47) = \underline{-0.82\text{ V}}$

(c) What gate capacitance would be measured at (i) high and (ii) low frequencies under these bias conditions. (6)

high f: modulate depletion region (inversion layer can't respond)

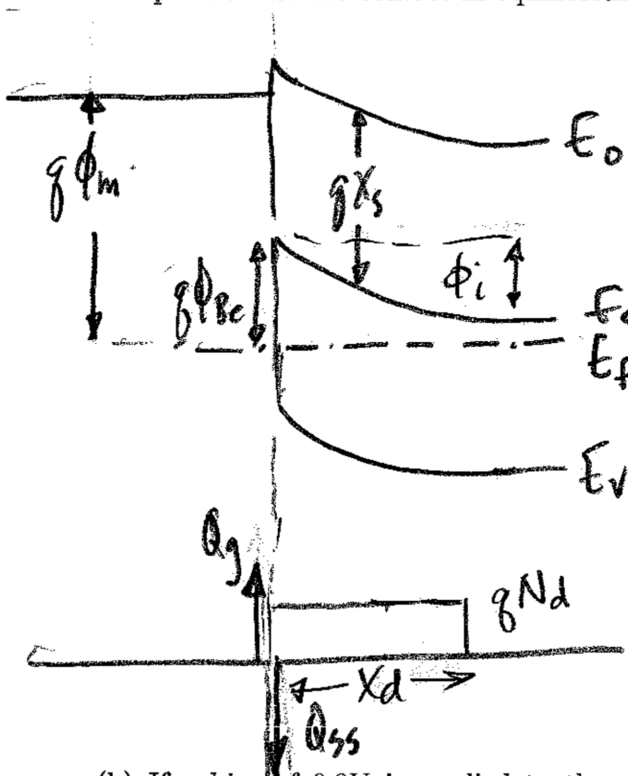
$x_d = Q_B'/qN_d = 3.44\times10^{-6}$ cm, $C_d' = \frac{K_s\epsilon_0}{x_d} = 3.0\times10^{-7}\frac{F}{cm^2}$

$C_{hf} = (C_d' C_{ox}')/(C_d' + C_{ox}') = 2.1\times10^{-7}$ F/cm^2

low f: modulate Q_i' $\quad C_{lf} = C_{ox}' = 6.9\times10^{-7}$ F/cm^2

4. A contact is made between tungsten ($\phi_m = 4.5\text{eV}$) and silicon ($\chi_s = 4.05\text{eV}$). The silicon is doped uniformly with $5 \times 10^{17}\text{cm}^{-3}$ of arsenic.

   (a) If a high density of surface states pins the Fermi level at 0.4eV above the valence band maxima, calculate semiconductor work function (ϕ_s), effective barrier for electrons from metal to semiconductor (ϕ_{Be}), and effective barrier for electrons from semiconductor to metal (ϕ_i) and sketch the band diagram (including vacuum level and with barriers indicated) and the charge density versus position for the contact in equilibrium. (11)



$$\frac{1}{q}(E_c - E_f)_{bulk} = \frac{kT}{q}\ln\left(\frac{3\times10^{19}}{5\times10^{17}}\right) = 0.11V$$

$$\frac{1}{q}(E_c - E_f)_{surface} = \frac{1}{q}(E_g - 0.4eV) = 0.72V$$

$$\phi_i = 0.72 - 0.11 = \underline{0.61V}$$

$$\phi_{Be} = \frac{1}{q}(E_g - E_f)_{surface} = \underline{0.72\,V}$$

$$\Phi_s = \chi_s + \frac{1}{q}(E_c - E_f)_{bulk} = \underline{4.16V}$$

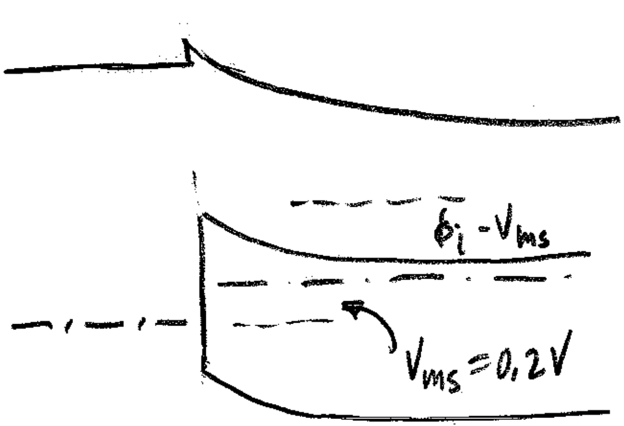
$$\phi_{Be} + \chi_s = 4.77\,V > \Phi_m = 4.5V$$

   (b) If a bias of 0.2V is applied to the metal relative to the semiconductor, calculate the junction capacitance per unit area and sketch the band diagram. (11)

$V_{MS} = 0.2V \Rightarrow$ fwd bias (metal acts like p-region)

$$V_s = \phi_i - V_{MS} = 0.61 - 0.2 = 0.41V$$

$$C_d' = \frac{K_s \epsilon_o}{X_d}\ ; \quad X_d = \sqrt{\frac{2K_s\epsilon_o V_s}{qN_d}} = 3.3\times10^{-6}\,cm$$



$$C_d = \frac{(11.7)(8.854\times10^{-14}F/cm)}{3.3\times10^{-6}cm} = 3.2\times10^{-7}\frac{C}{cm^2}$$

End Of Exam