Mean = 42.5 Range = [16:93]

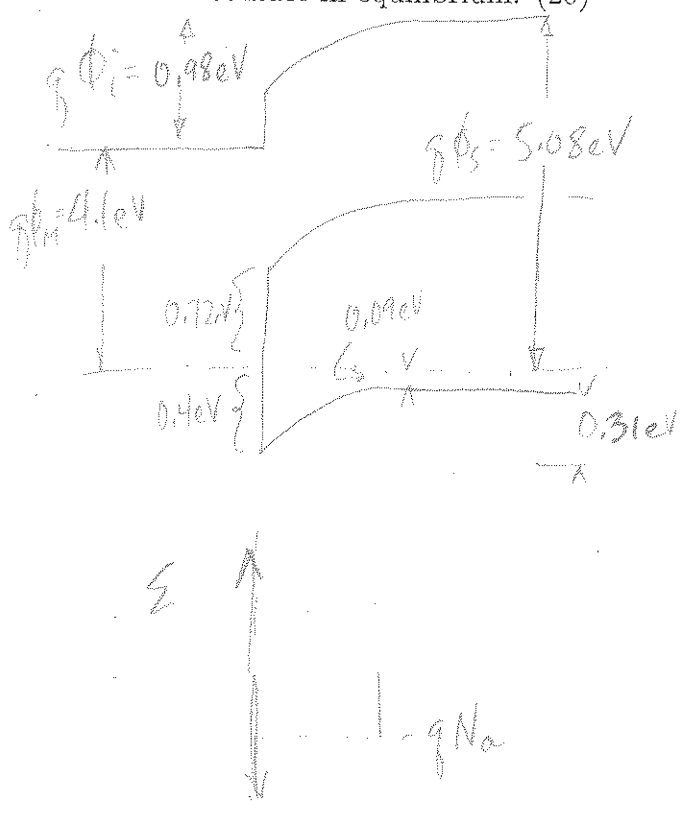
Name Solutions

Exam #2 — EE 482

Winter 2009

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.

1. A contact is made between silicon ($\chi_s = 4.05$eV) doped with $N_a = 10^{18}$cm^{-3} and aluminum ($\phi_m = 4.1$eV). A high density of surface states pins the Fermi level at 0.4eV above the valence band maxima. Calculate ϕ_s, ϕ_B and ϕ_i (ignoring any narrow tunnelable barrier associated with interface dipole layer) and sketch the band diagram (including vacuum level and with barriers indicated) and the charge density versus position for the contact in equilibrium. (20)



$$q\phi_s = 4.05\text{eV} + 1.12\text{eV} - \underbrace{kT\ln\left(\frac{N_V}{N_a}\right)}_{0.09\text{eV}}$$
$$= 5.08\text{eV}$$

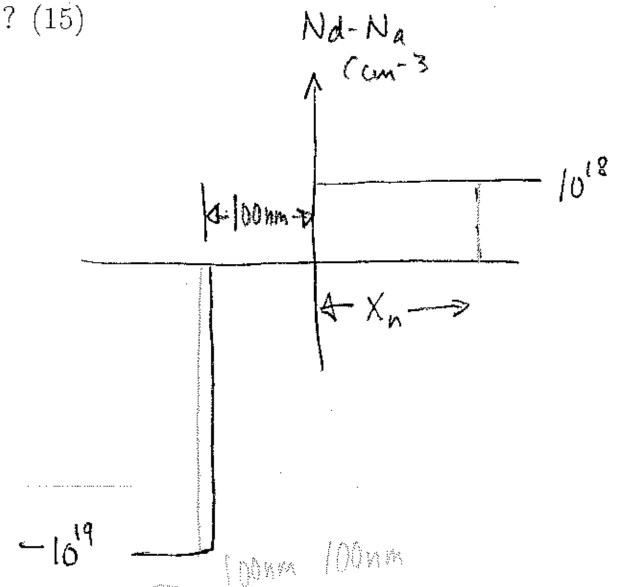
$q\phi_B = E_g - 0.4\text{eV} = 0.72\text{eV}$

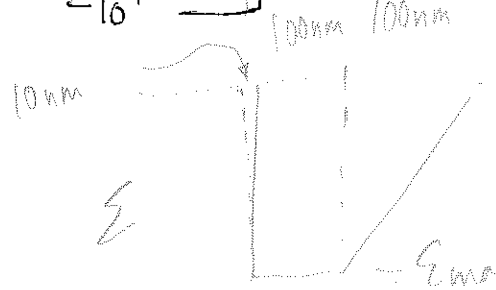
$q\phi_{Bh} = 0.4\text{eV}$

$\phi_i = \phi_M - \phi_s = 0.98V$, of this

$0.4 - 0.09 = 0.31$ is across semiconductor and rest is across interface dipole (surface states & metal)

2. If $x_n = 100\text{nm}$, what is the voltage dropped across the depletion region in pn junction with doping shown below (you may assume that width of heavily doped p-type depletion region is negligible)? (15)





$$-\mathcal{E}_{max} = -\frac{q(x_n)(10^{18}\,cm^{-3})}{K_s\epsilon_0} = \frac{(1.6\times10^{-19}C)(10^{-5}\ldots)(10^{18}cm^{-3})}{(11.7)(8.854\times10^{-14}\ldots)}$$

For $x_p \cong 0$,

$$\left[\phi_i - V_A\right] = \int \mathcal{E}\,dx = \left(10^{-5} + \frac{10^{-5}}{2}\right)\left|\mathcal{E}_{max}\right| \qquad = -1.54\times10^{6}\,\frac{V}{cm}$$

$$= 2.32\times10^{1}\,V = \underline{23.2\,V}$$

w/ $x_p = 10\text{nm}$ $\left(= x_n \frac{N_a}{N_d}\right)$, $\phi_i - V_A = \left(10^{-5} + \frac{10^{-5}}{2} + \frac{10^{-6}}{2}\right)\mathcal{E}_{max}$

$$= (1.55\times10^{-5}\,cm)(\mathcal{E}_{max}) = \underline{23.9V}$$

3. In an abrupt silicon p-n junction, $N_a = 5 \times 10^{18}\text{cm}^{-3}$, $N_d = 2 \times 10^{17}\text{cm}^{-3}$, $\tau_n = 0.25\mu\text{s}$, $\tau_p = 0.16\mu\text{s}$, $D_n = 4\,\text{cm}^2/\text{s}$ and $D_p = 2\,\text{cm}^2/\text{s}$ in the p-region and $\tau_n = 0.25\mu\text{s}$, $\tau_p = 0.16\mu\text{s}$, $D_n = 25\,\text{cm}^2/\text{s}$ and $D_p = 9\,\text{cm}^2/\text{s}$ in the n-region, $W_p = 100\text{nm}$ and $W_n = 500\mu\text{m}$. $T = 300\text{K}$. The applied voltage is 0.7 V. Assume recombination in depletion region can be neglected.

(a) Calculate the hole current density in n-region at edge of depletion region. (10)

$$\exp\left(\frac{0.7}{kT/q}\right) = 5.47\times10^{11} \qquad L_{pn} = \sqrt{(0.16\times10^{-6})(9)} = 12\times10^{-4}\,\text{cm} = 12\,\mu\text{m} \ll W_n = 500\,\mu\text{m}$$

$$p_{n0} = \frac{n_i^2}{N_d} = \frac{10^{20}}{2\times10^{17}} = 5\times10^{2}\,\text{cm}^{-3}$$

L_p

$$\Delta p_n(x_n) = 500 \times 5.47\times10^{11} = 2.73\times10^{14}\,\text{cm}^{-3}$$

$$J_p(x_n) = \frac{q\,\Delta p_n(x_n)\,D_{pn}}{L_{pn}} = \frac{(1.6\times10^{-19}\,\text{C})(2.73\times10^{14}\,\text{cm}^{-3})(9\,\frac{\text{cm}^2}{\text{s}})}{12\times10^{-4}\,\text{cm}} = 3.28\times10^{-1}\,\frac{\text{A}}{\text{cm}^2} \cdot 0.33\,\frac{\text{A}}{\text{cm}^2}$$

(b) Calculate electron current density at contact to p-region contact. (10)

$$J_n(-x_p-W_p) \simeq J_n(-x_p) = \frac{q\,\Delta n_p(-x_p)\,D_{np}}{W_p} = \frac{(1.6\times10^{-19}\,\text{C})(1.1\times10^{13}\,\text{cm}^{-3})(4)}{100\times10^{-7}\,\text{cm}} = 0.70\,\frac{\text{A}}{\text{cm}^2}$$

$L_{n_p} = \sqrt{(6.25)(4)}$ $10\mu m \gg W_p$

Short!

(c) Calculate electron current density at contact to n-region. (10)

$$J_n(x_p+W_p) = J_n(x_p) + J_p(x_p) = J_n(-x_n) + J_p(x_p) = 1.03\,\text{A}/\text{cm}^2$$

4. In a silicon ($\chi_s = 4.15\,\text{V}$) MOS capacitor with an n-type substrate and a heavily p-doped polysilicon gate ($E_f = E_v$), the substrate doping is $N_d = 10^{17}\text{cm}^{-3}$ and the oxide thickness is 5nm. The charge on the gate of $Q_g = -10^{-7}\,\text{C/cm}^2$.

   (a) Determine the state of the channel region (accumulation, flat-band, depletion, strong inversion, etc.). (10)

$Q_s > 0$ ... depletion ...

$$\phi_F = -\frac{kT}{q}\ln\left(\frac{10^{17}}{10^{10}}\right) = -0.42\,V$$

$$Q_{d,max} = \sqrt{2\epsilon_s\epsilon_0 q N_d |2\phi_F|}$$

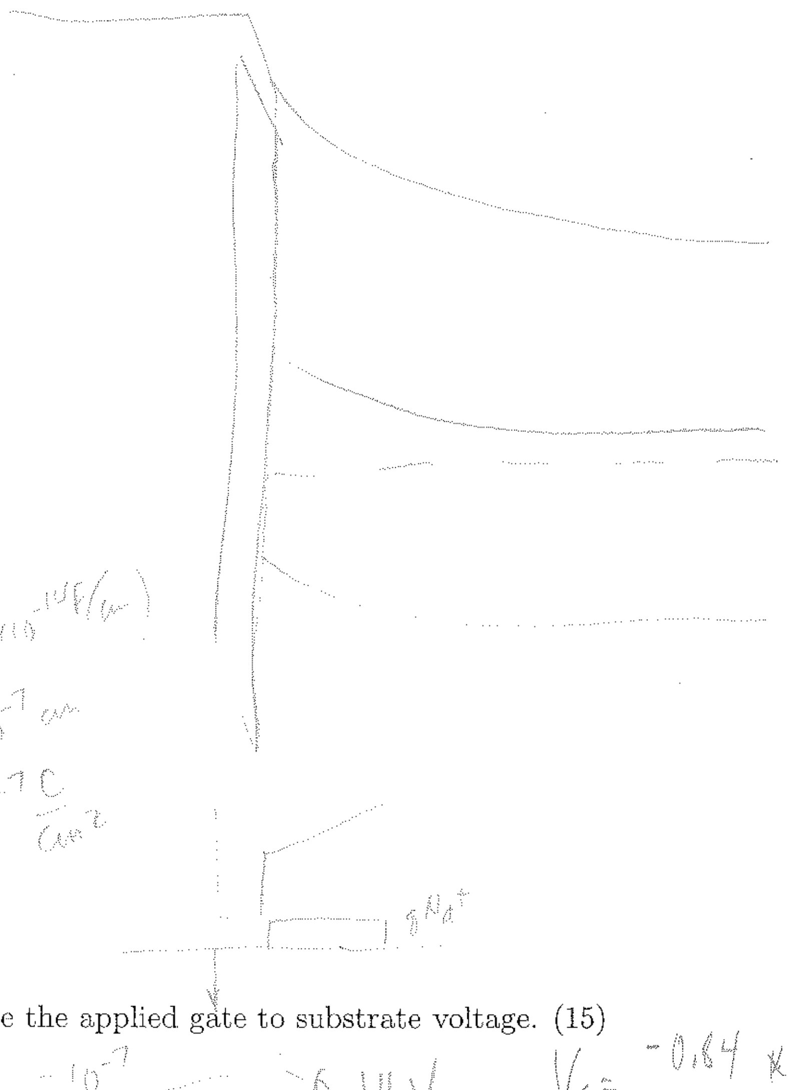
$$= \left[(2)(11.7)(8.854\times10^{-14}\tfrac{F}{cm})(1.6\times10^{-19}C)(10^{17}cm^{-3})(0.84V)\right]^{1/2} = 1.67\times10^{-7}\frac{C}{cm^2}$$

$$Q_s = 10^{-7}\,C/cm^2 < Q_{d,max} \Rightarrow \text{Depletion}$$

   (b) Sketch the charge density, electric field and energy band diagram for the system. (10)

$\phi_{MS} = 1V$

$$C_{ox}' = \frac{\epsilon_{ox}\epsilon_0}{x_{ox}} = \frac{(3.9)(8.854\times10^{-14}F/cm)}{5\times10^{-7}cm} = 6.9\times10^{-7}\frac{C}{cm^2}$$



   (c) Determine the applied gate to substrate voltage. (15)

$$V_{ox} = +\frac{Q_s}{C_{ox}} = \frac{-10^{-7}}{6.9\times10^{-7}C/cm^2} = -0.14V \qquad V_s = -0.84\times\left(\frac{1}{1.67}\right)^2 = -0.30$$

$$V_{gb} = \Phi_{MS} + V_{ox} + V_s = 1V - 0.14V - 0.3V = 0.56V$$