Equation Sheet

Please tear off this page and keep it with you

General Semiconductor:

$n_0 = n_i e^{\left(\frac{(E_F - E_{Fi})}{kT}\right)}$ $p_0 = n_i e^{\left(\frac{(E_{Fi} - E_F)}{kT}\right)}$ $n_i^2 = N_C N_V e^{\left(\frac{-E_g}{kT}\right)} = n_0 p_0$ $V = IR$ $L_{n,p} = \sqrt{D_{n,p}\tau_{n,p}}$

$J_{drift} = \sigma E$ $\sigma = e(\mu_n n + \mu_p p) = \frac{1}{\rho}$ $J_{diff} = eD_n \frac{dn}{dx} - eD_p \frac{dp}{dx}$ $J = \frac{I}{A}$ $\frac{D}{\mu} = \frac{kT}{e}$ $\mu = \frac{e\tau_c}{m_c^*} = \frac{g_m L^2}{V_{DS} C_{ox}}$

pn Junctions:

$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right)$ $x_n = \left[\frac{2\varepsilon_s \varepsilon_0}{e}\frac{N_a}{N_d(N_a + N_d)}V_{bi}\right]^{1/2}$ $x_p = \left[\frac{2\varepsilon_s \varepsilon_0}{e}\frac{N_d}{N_a(N_a + N_d)}V_{bi}\right]^{1/2}$

$W = \left[\frac{2\varepsilon_s \varepsilon_0}{e}\frac{N_a + N_d}{N_a N_d}V_{bi}\right]^{1/2}$ $W_{RB} = \left[\frac{2\varepsilon_s \varepsilon_0}{e}\frac{N_a + N_d}{N_a N_d}(V_{bi} + V_R)\right]^{1/2}$ $n_p(-x_p) = n_{p0} e^{\left(\frac{eV_a}{kT}\right)}$ $p_n(x_n) = p_{n0} e^{\left(\frac{eV_a}{kT}\right)}$

$\delta n_p(x) = n_{p0}\left[e^{\left(\frac{eV_a}{kT}\right)} - 1\right] e^{\left(\frac{x_p + x}{L_n}\right)}$ $\delta p_n(x) = p_{n0}\left[e^{\left(\frac{eV_a}{kT}\right)} - 1\right] e^{\left(\frac{x_n - x}{L_p}\right)}$ $E_{Fn} = E_{Fi} + kT\ln\left(\frac{n}{n_i}\right)$ $E_{Fp} = E_{Fi} - kT\ln\left(\frac{p}{n_i}\right)$

$J_{ID} = J_S\left(e^{\left(\frac{eV_a}{kT}\right)} - 1\right)$ $J_S = \frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}$ $J_{rec} = \frac{eWn_i}{2\tau_0} e^{\left(\frac{eV_a}{2kT}\right)}$ $g_d = \frac{1}{r_d} = \frac{I_{DQ}}{V_t}$ $C_d = \frac{1}{2V_t}\left(I_{p0}\tau_{p0} + I_{n0}\tau_{n0}\right)$

MOS Capacitors:

$C'(acc) = C_{ox} = \frac{\varepsilon_{ox}\varepsilon_0}{t_{ox}}$ $C'(depl) = \frac{\varepsilon_{ox}\varepsilon_0}{t_{ox} + \left(\frac{\varepsilon_{ox}}{\varepsilon_s}\right)x_d}$ $C'_{\min} = \frac{\varepsilon_{ox}\varepsilon_0}{t_{ox} + \left(\frac{\varepsilon_{ox}}{\varepsilon_s}\right)x_{dT}}$ $C'_{FB} = \frac{\varepsilon_{ox}\varepsilon_0}{t_{ox} + \left(\frac{\varepsilon_{ox}}{\varepsilon_s}\right)\sqrt{V_t\left(\frac{\varepsilon_s \varepsilon_0}{eN_{a,d}}\right)}}$

$V_{FB} = \phi_{ms} - \frac{Q'_{ss}}{C_{ox}}$ $e\phi_s = E_{Fi}\big|_{bulk} - E_{Fi}\big|_{surf}$ $V_{TN} = \frac{\left|Q'_{SD}(\max)\right|}{C_{ox}} + V_{FB} + 2\phi_{fp}$ $V_{TP} = \frac{-\left|Q'_{SD}(\max)\right|}{C_{ox}} + V_{FB} - 2\phi_{fn}$

p-type: $\phi_{ms} = \phi'_m - \left(\chi' + \frac{E_g}{2e} + \phi_{fp}\right)$ $\phi_{fp} = V_t\ln\left(\frac{N_a}{n_i}\right)$ $x_d = \left(\frac{2\varepsilon_s \varepsilon_0 \phi_s}{eN_a}\right)^{1/2}$ $x_{dT} = \left(\frac{4\varepsilon_s \varepsilon_0 \phi_{fp}}{eN_a}\right)^{1/2}$ $\left|Q'_{SD}(\max)\right| = eN_a x_{dT}$

n-type: $\phi_{ms} = \phi'_m - \left(\chi' + \frac{E_g}{2e} - \phi_{fn}\right)$ $\phi_{fn} = V_t\ln\left(\frac{N_d}{n_i}\right)$ $x_d = \left(\frac{2\varepsilon_s \varepsilon_0 \phi_s}{eN_d}\right)^{1/2}$ $x_{dT} = \left(\frac{4\varepsilon_s \varepsilon_0 \phi_{fn}}{eN_d}\right)^{1/2}$ $\left|Q'_{SD}(\max)\right| = eN_d x_{dT}$

MOSFETs:

$g_m = \frac{\delta I_D}{\delta V_{GS}}$ $SS = \left(\frac{\delta(\log(I_D))}{\delta V_{GS}}\right)^{-1}$ $f_T = \frac{g_m}{2\pi(C_{gsT} + C_M)} = \frac{g_m}{2\pi C_G}$ $C_M = C_{gdT}(1 + g_m R_L)$

p-type: $I_D = \frac{W\mu_p C_{ox}}{2L}\left[2(V_{SG} + V_T)V_{SD} - V_{SD}^2\right]$ $I_D(sat) = \frac{W\mu_p C_{ox}}{2L}(V_{SG} + V_T)^2$ $K_p = \frac{W\mu_p C_{ox}}{2L}$ $k'_p = \mu_p C_{ox}$

n-type: $I_D = \frac{W\mu_n C_{ox}}{2L}\left[2(V_{GS} - V_T)V_{DS} - V_{DS}^2\right]$ $I_D(sat) = \frac{W\mu_n C_{ox}}{2L}(V_{GS} - V_T)^2$ $K_n = \frac{W\mu_n C_{ox}}{2L}$ $k'_n = \mu_n C_{ox}$

$k = 8.62x10^{-5} eV/K = 1.38x10^{-23} J/K$ $h = 4.14x10^{-15} eV\cdot s = 6.63x10^{-34} J\cdot s$ $\hbar = \frac{h}{2\pi}$

$q = 1.602x10^{-19} C$ Si at T = 300 K: n_i = 1.5x10^{10} cm^{-3}, E_g = 1.12 eV, ε_s = 11.7 SiO_2: ε_{ox} = 3.9

kT = 0.026 eV at room temperature ε_0 = 8.85x10^{-14} F/cm

Exam 2

Semiconductor Devices

Name: ___________________________________ Net ID: ______________

- **5 questions.**
- **20 points per question.**
- **Partial credit will be given when possible (MUST show work).**
- **Please write neatly (legibly). When given, write final answers in the provided boxes.**
- **Show your work (NEATLY) whenever it is possible (use the back of pages if needed)!**

Good luck!

1) pn Junction Diodes

Consider a silicon pn junction diode with area of 10^{-4} cm^2 at T = 300K and the following parameters:

p-side	n-side
$N_a = 10^{17}$ cm^{-3}	$N_d = 10^{14}$ cm^{-3}
$\tau_n = 10^{-7}$ s	$\tau_p = 10^{-6}$ s
μ_n = 1200 cm^2/V-s	μ_n = 800 cm^2/V-s
μ_p = 400 cm^2/V-s	μ_p = 300 cm^2/V-s

a. Sketch the thermal equilibrium energy band diagram for this diode in the space provided. Be sure to include an accurate value (and reasonably accurate sketch) for $|E_F - E_{Fi}|$ on both sides of the junction and of V_{bi}. Show your calculations and label E_c, E_v, E_F, and E_{Fi}.

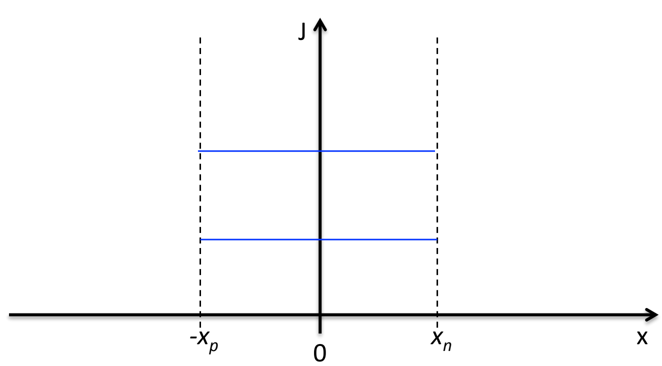
Take each box to be 0.25 eV on all sides

b. Now sketch the energy band diagram under an applied forward bias, V_a= 0.25 V. Be sure to indicate V_a in some fashion on your diagram and sketch in the quasi-Fermi levels.

c. Calculate the amount of current (I) flowing through the diode if V_a = 0.25 V.

I =

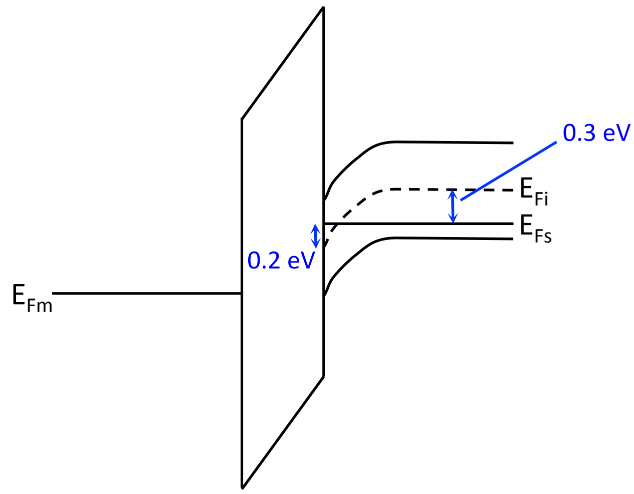
d. Complete the qualitative sketch (given on the right) of the current density in the diode, including the curves for J_{total}, J_n and J_p on each side of the junction and label $J_n(-x_p)$ and $J_p(x_n)$.



2) MOS Capacitors

Given the energy band diagram of an MOS capacitor on the right, with the parameters indicated below, answer the questions.

$V_{FB} = 0.06$ V, $Q_{ss}' = 0$, $t_{ox} = 7$ nm, $f = 10$ Hz, $\phi_f = -0.3$ V



a. On the given band diagram, sketch in the applied gate voltage, V_G.

b. What is the surface potential?

c. What is the applied gate voltage, V_G?

d. What is the doping type and density?

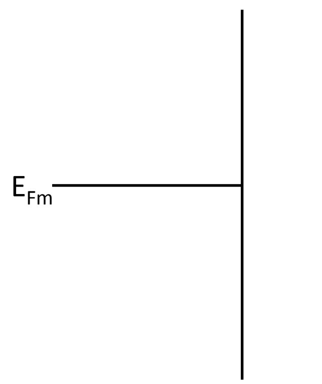
e. Calculate the threshold voltage, V_T. Is this MOS capacitor operating in strong inversion?

f. Using the partially filled out band diagram, sketch the remainder of the band diagram for when the MOS capacitor is at V_G = 0 V, labeling E_{Fs}, E_{Fi}, E_C, E_V, and ϕ_s.

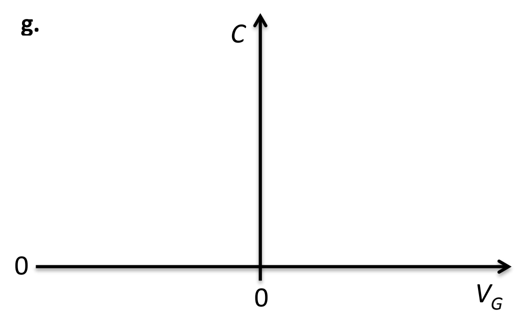
g. Sketch the C-V curve for this capacitor on the axes below and label the point at which the capacitor is operating along with V_T, V_{FB}, C_{ox}, and C_{min}.

***Show your work (neatly) whenever possible (use back of page if needed)!**

f.



g.



b. $\phi_s =$

c. $V_G =$

d. $type =$

$N =$

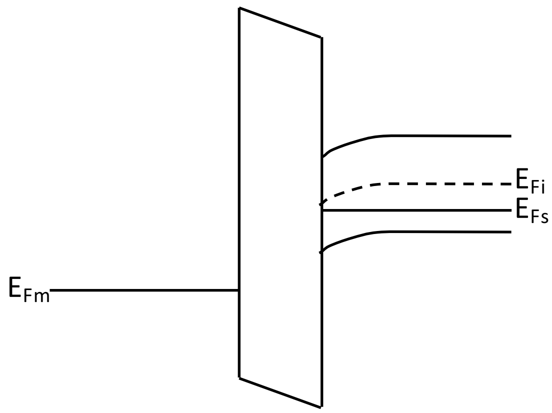
e. $V_T =$

Strong Inversion? =

3) MOS Capacitor – CONCEPTUAL

Answer the questions in the spaces provided:

For the MOS capacitor band diagram on the left:



a. Is the capacitor in thermal equilibrium? ________________

b. Is the semiconductor in thermal equilibrium? ________________

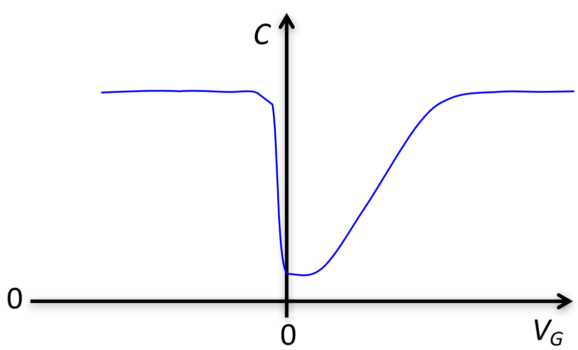
c. What type of semiconductor is this? ________________

d. Does $\phi_{ms} = 0$ for this capacitor? ________________

e. What polarity V_G (positive or negative) is needed to operate the capacitor in the flat-band mode? ________________

f. Sketch onto the band diagram what would happen if $V_G = +|\phi_f|$ were applied, showing all relevant changes that would take place.

g. What mode would the capacitor be operating in with this applied voltage (from part **f**)? ________________



For the MOS capacitor C-V curve on the left:

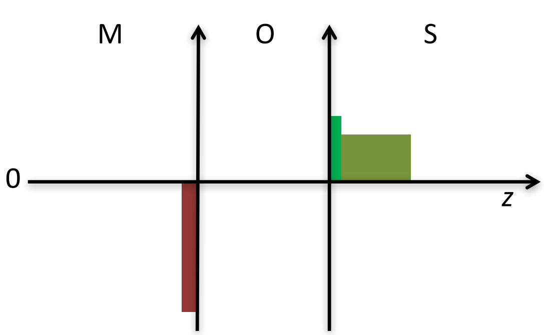
h. Is the capacitor operating at low or high *f*? ________________

i. What type of semiconductor is this? ________________

j. Indicate on the curve where the depletion mode of operation is taking place.

k. Redraw the C-V curve for the case of having some negative fixed charges added to the oxide.

l. What is the approximate threshold voltage for this capacitor? ________________



For the MOS capacitor block charge diagram:

m. What type of semiconductor is this? ________________

n. What mode is this capacitor operating in? ________________

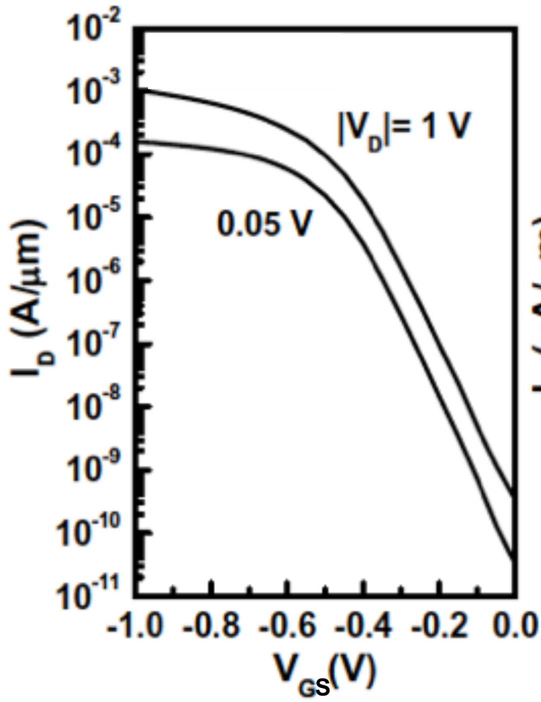
o. On the diagram, sketch in what would happen as a small, high frequency ac signal is applied.

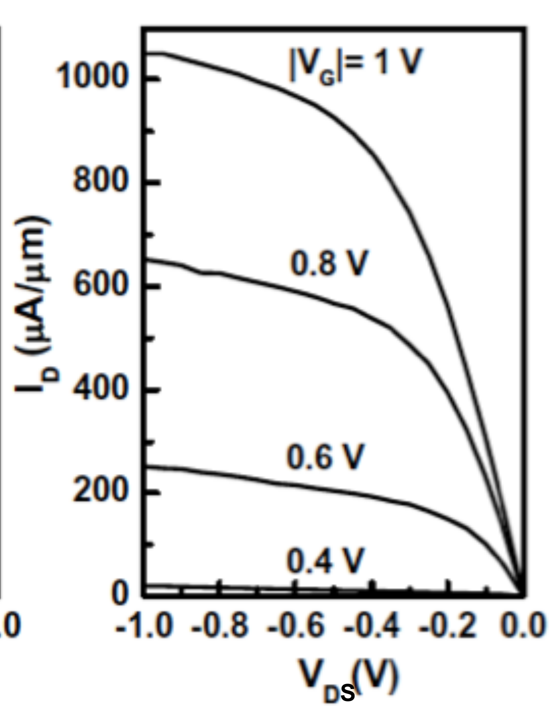
p. On the diagram, sketch in what it would look like to have some positive fixed charge present in the oxide.

q. From this diagram, can you tell whether or not $V_{FB} = 0$ V? ________________

4) MOSFETs

Consider a Si MOSFET with the characteristics shown below. Label the type of characteristics that each plot shows on the lines below the plots.





__________________ characteristics ___________________ characteristics

The voltage, V_{GS} is connected with the positive terminal to the gate of the MOSFET and the voltage, V_{DS} has the positive terminal to the drain. The device has V_{DD} = 1 V with V_T = -0.5 V, t_{ox} = 2 nm, W = 1 µm, $k_n' = k_p'$ = 0.50 mA/V^2, and a load resistance of 125 Ω. Answer the questions or extract the parameters below and, when possible, *show how each was extracted on the plots*.

a) Subthreshold swing = _________

b) Transconductance = ________

c) On-current = ________

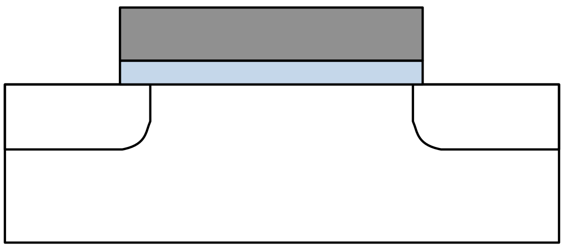
d) Is the MOSFET n-type or p-type? _________

e) Mobility = ________

f) In the space below, sketch the cross-section of this MOSFET, including the source, drain, gate, and appropriate labels for doping.

5) MOSFETs – CONCEPTUAL

Answer the questions in the spaces provided:



For the MOSFET schematic on the left:

a. If this is an p-type MOSFET, label the source, drain, and substrate regions with the appropriate doping.

b. Sketch in the depletion region and inversion layer for the condition when the MOSFET is operating in the linear region.

c. Will there be overlap capacitance in this MOSFET?

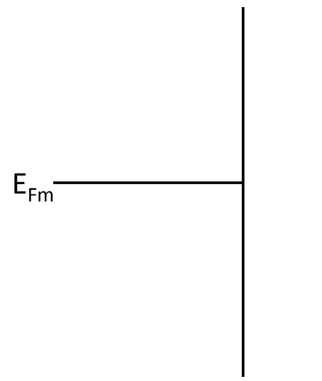
____

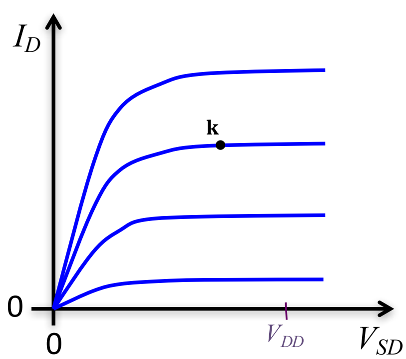
d. Which will be greater, C_{gsp} or C_{gdp}?

____

e. On the schematic above, identify the dimension L.

f. In the band diagram started to the right, sketch the MOS capacitor portion of this MOSFET under the above conditions, labeling E_{Fs}, E_{Fi}, E_C, E_V, V_{SG}, and ϕ_s.





For the curves in the plot to the left:

g. Can the V_T be accurately determined from this plot?

____

h. What type of MOSFET is this?

____

i. Sketch the V_{DS} (sat) line on the plot.

j. If the 2nd curve from the top is from $V_{GS} = V_{DD}$, indicate the on-current on the plot.

k. In the empty schematic given below, sketch the MOSFET from this plot operating at the indicated point labeled 'k.' On your sketch, label the source, drain, and substrate regions with appropriate doping and include the depletion region and inversion layer. If applicable, label L, ΔL, and include the capacitances C_{gd}, C_{gdp}, C_{gs}, and C_{gsp}.