University of California, Berkeley *Spring 2020*
EE 105 *Prof. A. M. Niknejad*

Midterm Exam: Open book and open notes, no Internet

Name (Last, First)

SID

HONOR CODE Copy the following statements into the box below and sign your name: I will respect my classmates and the integrity of this exam by following this honor code. I affirm:

1. All of the work submitted here is my original work.
2. I did not reference any sources on the internet.
3. I did not collaborate with any other human being on this exam.

Notes:
The resistance of a material is related to the physical dimensions and resistivity by

$$R = \frac{\rho L}{tW} = \frac{\rho}{t}\frac{L}{W} = R_{sq}\frac{L}{W}$$

The capacitance of a parallel plate structure is given by (per unit area)

$$C' = C/A = \frac{\epsilon}{d}$$

The conductivity of a material depends on charge density (n and p), mobility $\mu_{n,p}$, and charge of carriers q_e:

$$\sigma = q_e(\mu_n n + \mu_p p)$$

where $q_e = 1.60217662 \times 10^{-19}$C for an electron. The mobility is given by

$$\mu = \frac{q\tau}{m}$$

where q is the charge of the particle, τ is the average time between collisions, and m is the effective mass. Drift current $J = \sigma E$ flows due to fields. Diffusion currents flow due to concentration gradients. For a concentration gradient of positive charges, we have

$$J_{diff} = -qD_p \frac{dp}{dx}$$

where D_p is the diffusion coefficient, which is related to the mobility by $kT/q = D/\mu$. For silicon at room temperature, $kT/q = 26\text{mV}$, and assume $n_i = 10^{10}\text{cm}^{-3}$. For n-type materials, the potential ϕ_n defined with respect to intrinsic silicon is defined by

$$n = n_i e^{q\phi_n/kT}$$

Likewise, for p-type materials:

$$p = n_i e^{-q\phi_p/kT}$$

For a pn-junction, the equilibrium depletion region widths are given by

$$x_n(V_D) = \sqrt{\frac{2\varepsilon_s(\varphi_{bi} - V_D)}{qN_d}\left(\frac{N_a}{N_a + N_d}\right)} = x_{n0}\sqrt{1 - \frac{V_D}{\varphi_{bi}}}$$

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In the presence of excess minority carriers in a semiconductor, the continuity equation dictates that (for holes, similar for electrons)

$$\frac{dJ_p}{dx} = q\frac{\Delta p}{\tau_p}$$

where τ_p is the minority carrier lifetime. The diffusion length (for holes) is defined by $L_p^2 = \tau_p D_p$ and similarly for electrons. Boltzmann's Law:

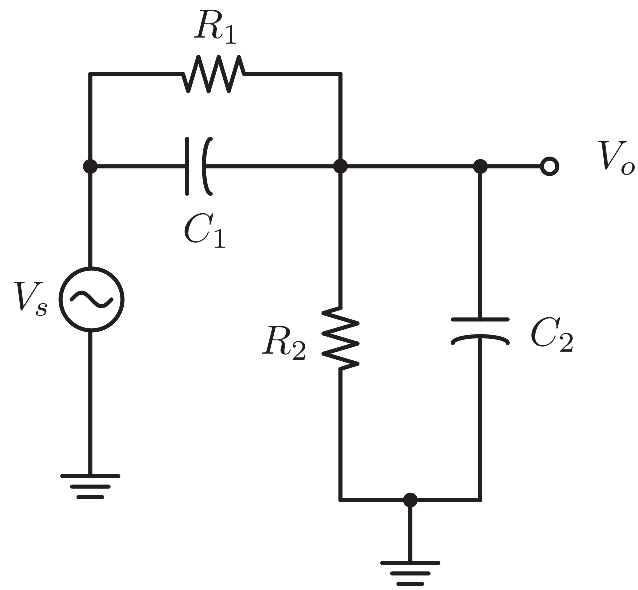
$$\frac{p_2}{p_1} = e^{-(Barrier\ Energy)/kT}$$

The diode I-V relation is given by

$$I_D + i_D = I_S\left(e^{\frac{q(V_d + v_d)}{kT}} - 1\right)$$

Electron charge $q = -1.6 \times 10^-19\text{C}$, silicon dielectric permittivity is given by $11.7\epsilon_0$ and silicon dioxide is $3.9\epsilon_0$. $\epsilon_0 = 8.854e - 12\text{F/m}$.

1. (25 points) Consider a circuit with input voltageV_s and output voltage V_o:



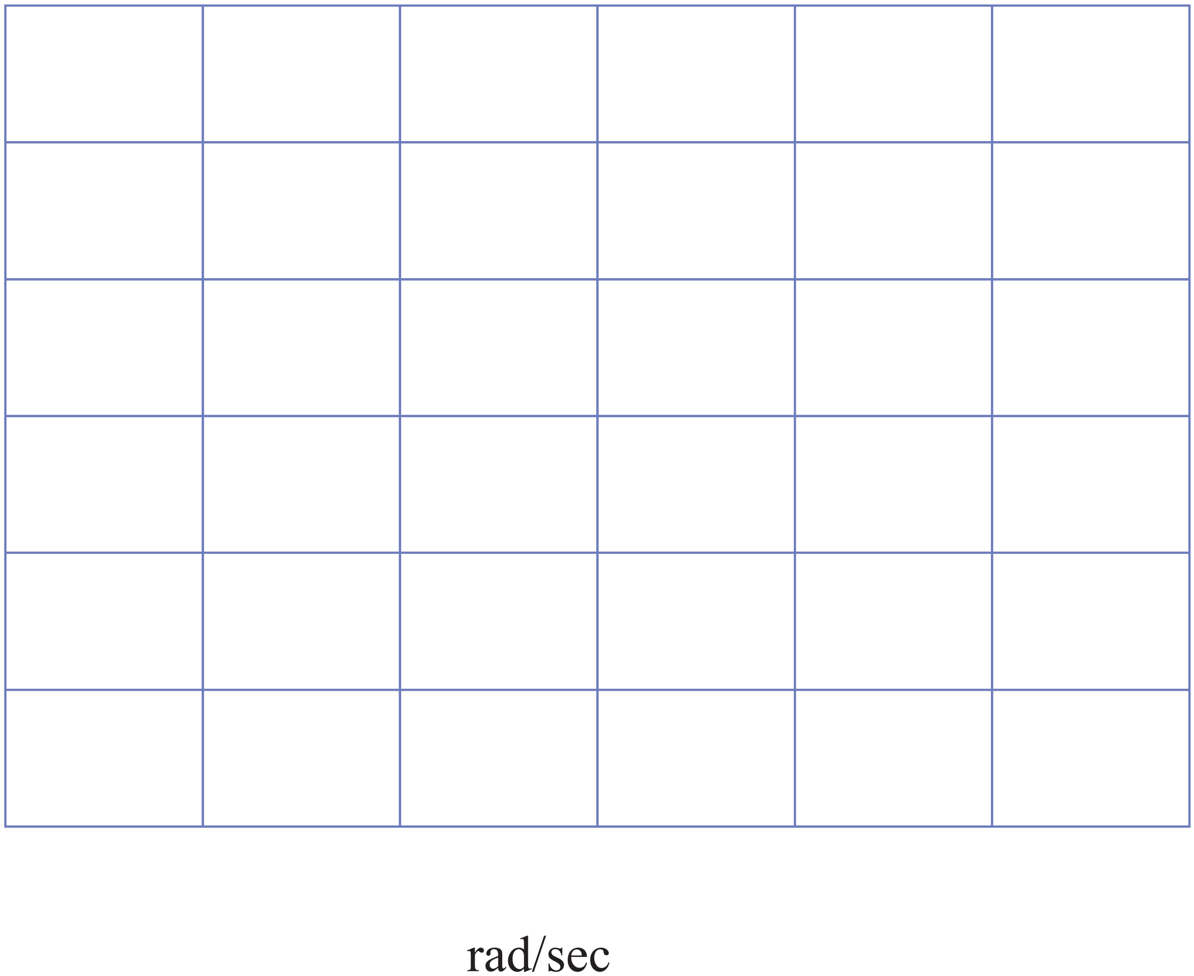
(a) (3 points) Without doing any “math” (lots of equations), what’s the DC gain?

(b) (3 points) Again, without doing any “math” (lots of equations), what’s the gain at very high frequencies $f \to \infty$?

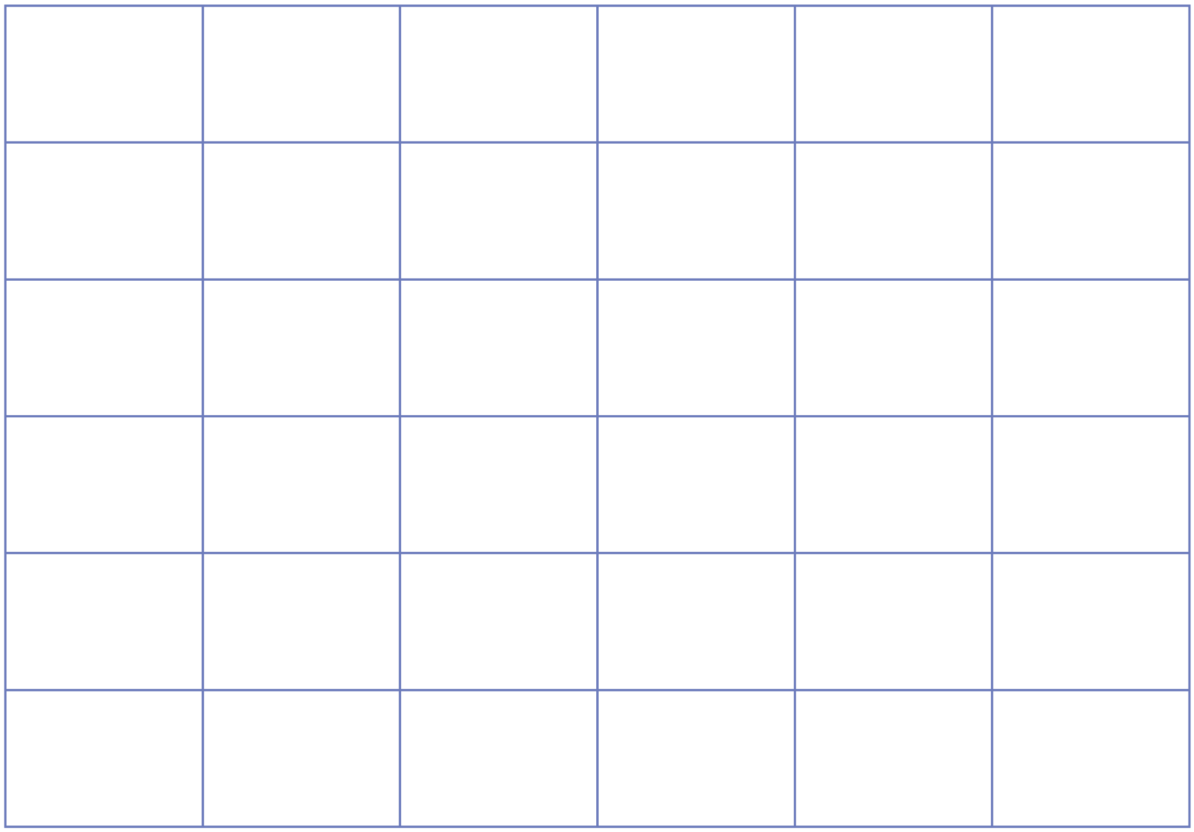
(c) (4 points) Find the transfer function V_o/V_i. Make sure that your "inspection analysis" from the previous two parts matches your calculations.

(d) (2 points) Identify the the poles and zeros?

(e) (4 points) Draw the magnitude Bode plot using the template. Clearly label the graph with the location of the poles and zeros, including the x-axis intercept point and any breakpoints. You may approximate the plot by using straight lines.

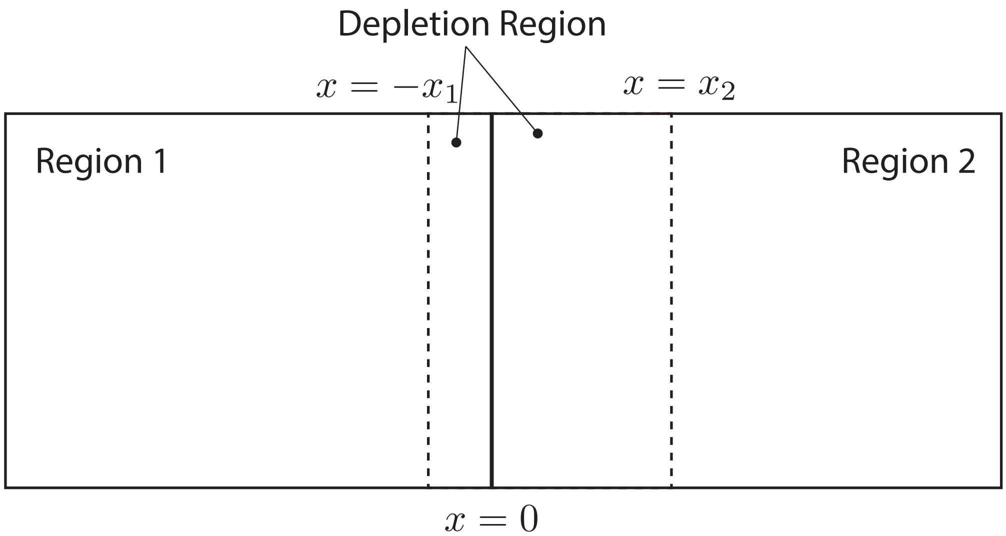


(f) (4 points) Draw the phase Bode plot using the template. Clearly label the graph. You may approximate the plot by using straight lines.



rad/sec

(g) (5 points) How much average power is dissipated in the circuit as a function of frequency normalized to a source $V_{in} = 1\text{V}$. Make sure you setup the problem correctly to get partial credit.



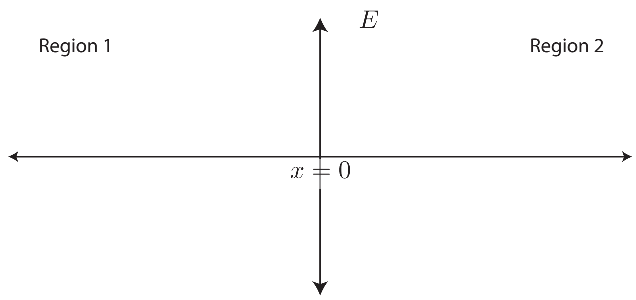
2. (25 points) Consider the pn-junction shown above at equilibrium (zero bias). The p-region is doped with 10^{16}cm^{-3} dopants and the n-region is doped with a concentration of 10^{17}cm^{-3} dopants.

   (a) (7 points) Label where the p and n regions (region 1 or 2). The dashed lines indicate the border of the depletion region under the depletion approximation. Briefly explain your logic.

   Region 1:
   Region 2:
   Reason:

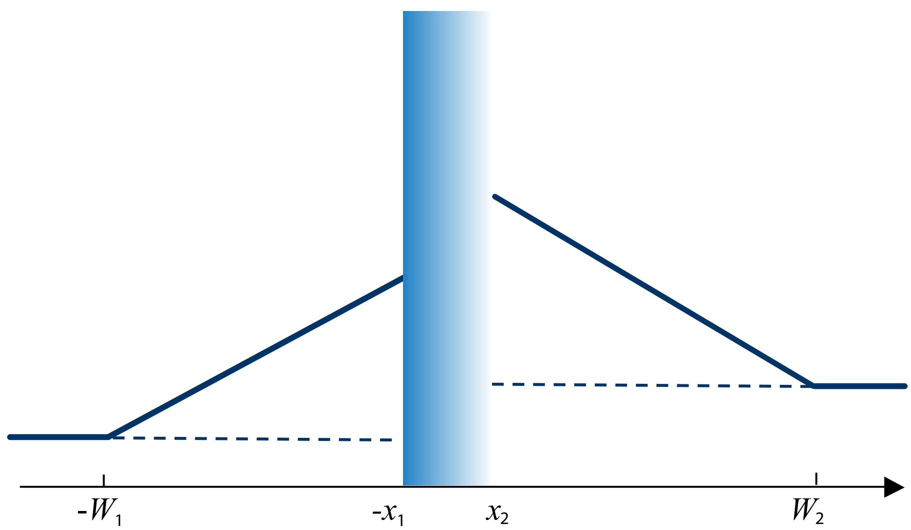
(b) (6 points) Indicate the charge in each depletion region by using circles "plus" and "minus" signs to indicate ionized (immobile) dopants. Re-use the figure above.

(c) (6 points) Suppose the peak electric field in the structure is measured at -2MV/m. Draw the electric field strength on the provided graph and indicate the location and direction of the peak electric field by labeling the graph with $x = x_1$ and $x = x_2$. Note that you must label the x-axis to receive credit.



(d) (6 points) Calculate the applied bias if $|x_1| + |x_2| = 0.2\mu\text{m}$.

3. (30 points) A pn-junction is formed with one region doped with $N_A = 10^{17}\text{cm}^{-3}$ acceptor dopants and the other side doped with $N_D = 10^{15}\text{cm}^{-3}$ donor dopants. A voltage of magnitude $V_D = 0.7\text{V}$ is applied to the junction and the resulting minority carrier distribution is shown in the figure above. $W_1 = .25\mu\text{m}$ and $W_2 = 0.8\mu\text{m}$. For this problem assume electrons have a mobility of $\mu_n = 1000\text{cm}^2/\text{V}\cdot\text{s}$ and holes have a mobility of $\mu_p = 500\text{cm}^2/\text{V}\cdot\text{s}$. Assume the device has a cross-sectional area of $10\mu\text{m}^2$ (into the page).



(a) (2 point) What region of operation is the diode in ? In other words, what is the sign of V_D? Explain.

(b) (8 points) Label the graph above: (i) You must label p and n regions on the graph, (ii) Indicate which curve is the electron profile and which curve is the hole profile. (iii) Calculate and label n_{p0} and p_{n0} .

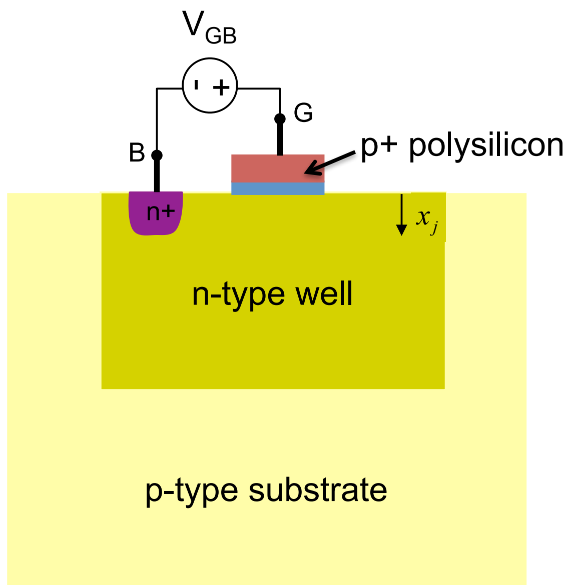
(c) (5 points) Calculate the concentration of minority carriers n_p and p_n at the depletion edge. Also label the graph.

(d) (5 points) Calculate the current flow due to diffusion. Use $kT/q = D/\mu$.

(e) (5 points) Qualitatively, discuss the origin of the diode saturation current I_S. First explain why a current flows when the diode is reverse biased. Next discuss why the current is nearly independent of the reverse bias. Finally, discuss the temperature dependence of th saturation current.

(f) (5 points) If a light source with a photon flux of $G_L = 10^{15}\text{photons} \cdot \text{cm}^{-3}$ uniformly illuminates the sample, how does this change the saturation current? You may answer this question qualitatively.

4. (20 points) The following is a cross-section of a MOS Capacitor in a silicon wafer. For this problem, use Φ_n = 300mV, Φ_{p+} = -550mV, V_{DD} = 0.8V, V_T = -0.45V, t_{ox} = 15nm. Pay careful attention to voltage polarity!



(a) (4 points) What bias voltage V_{GB} do you need to apply in order to achieve the flat-band condition (no charge in the capacitor)?

(b) (5 points) You decide to use this capacitor to filter noise on the supply V_{DD} (also known as decoupling). To do this you hook up the gate (G) to V_{DD} and the body (B) to ground. What region of operation is the MOS capacitor in? Justify your answer (a guess without justification will receive no credit).

(c) (5 points) You compare this with the opposite configuration of hooking up the gate (G) to ground and the body (B) to V_{DD}. What region of operation is the MOS capacitor in now? Justify your answer (a guess without justification will receive no credit).

(d) (6 points) Which configuration gives the highest capacitance per unit area? Calculate the capacitance per unit area in this preferred configuration.