University of California at Berkeley
College of Engineering
Dept. of Electrical Engineering and Computer Sciences

EE 105 Midterm

Spring 2004 Prof. John S. Smith March 10, 2004

Your Name: ______________________________

Student ID Number: ___-_.________________

Guidelines

Closed book and notes; one 8.5" x 11" page (one side) of *your own notes* **is** allowed.
You may use a calculator.
Do not unstaple the exam.
Show all your work and reasoning on the exam in order to receive full or partial credit.

Score

Problem	Points Possible	Score
1	30	
2	25	
3	25	
4	25	
Total	105	

1. (a) [5 points] The source and drain of a NMOS transistor are doped with donors, and the body is doped with acceptors. Explain why there is little current from the source to the body, or the drain to the body under normal operating conditions. Give an example of an abnormal condition which would give a larger current from the source to the body.

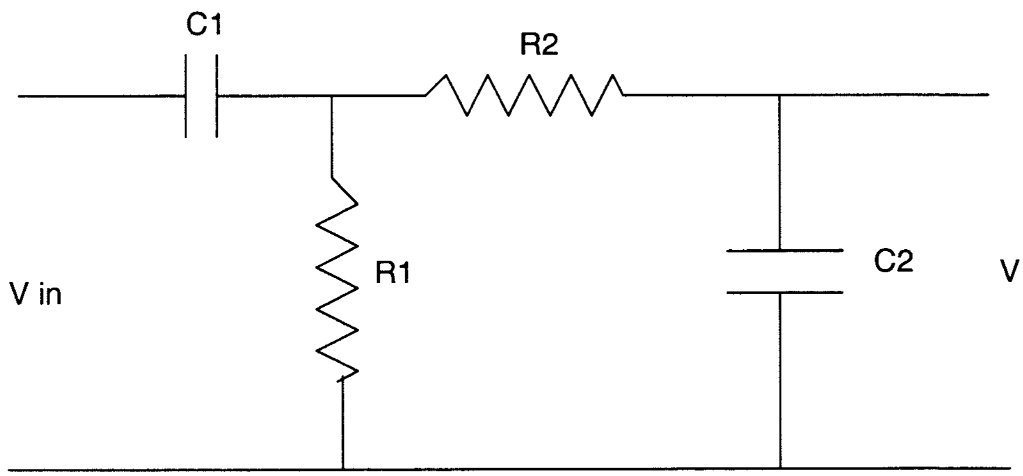
(b) [5 points] For a silicon PN junction at room temperature which has one side P doped to a concentration of 10^{18} per cubic cm and the other side N doped to a concentration of 10^{16} per cubic cm, find the depletion depth into both the P side and into the N side.

(c) [5 points] What applied voltage would give the flat band condition in a MOS capacitor in which the material above the oxide is doped to 10^{18} per cubic cm with acceptors, and the below the oxide is doped with donors to 10^{17} per cubic cm? If the voltage is positive for the upper contact, give it as a positive number, if the voltage is negative for the upper contact; give it as a negative voltage.

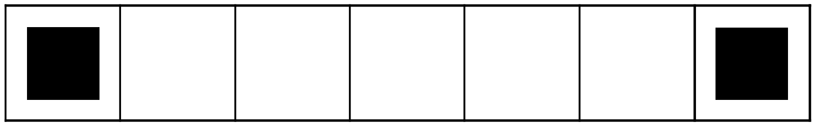
(d) [5 points] In a silicon resistor made from N doped silicon doped to 10^{18} per cubic cm, with a cross section 1 micron by 0.1 micron, what is the maximum current which can flow? What strength of E field will produce that current?

(e) [5 points] Explain why the small signal capacitance per unit area for a MOS device is the same in inversion as it is in accumulation.

(f) [5 points] In the following circuit, what is the phase shift from the input voltage to the output voltage at frequencies which are high compared to $(R_1C_1)^{-1}$ and yet low compared to $(R_2C_2)^{-1}$, assuming $R_2 >> R_1$? In that frequency range, what is the relationship between Vout and Vin?



2. IC resistors: Starting with a substrate which is doped with Boron to a concentration of 1×10^{17} ions per cubic centimeter, a resistor is made by implanting a dose of 4×10^{13} arsenic ions per square centimeter into, and then the implanted ions are diffused to a depth of 0.5 microns.



(a) [4 points] Find the number of electrons and holes in the **part** of the silicon which forms the resistor.

(b) [4 points] Find the resistivity in ohms per square of the resulting layer

(c) [4 points] Find the resistance of the structure above, neglecting the resistance of the end squares with the contacts.

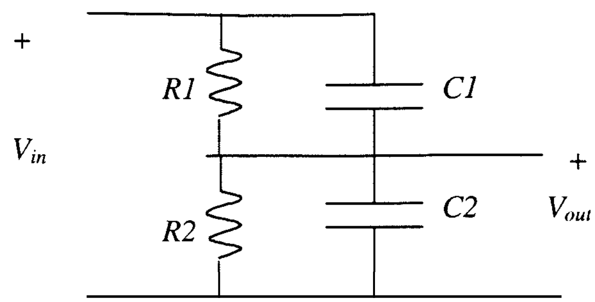
(d) [4 points] If the diffusion time was extended, so that the ions were driven in to a depth of 1 micron, would the resistance go up or down? What factors would be important to consider?

(e) [3 points] What happens if the implanted dopants were diffused in to a depth of **4** microns?

(f) [3 points] Recalculate the resistance of the channel with the implanted dopants driven in to the **2** micron depth, taking into consideration the factors that you mention in **part** d.

(g) [3 points] Explain what could happen to the resistor from part (e) if there is a variation of **+/-** 10%in the implant dose.

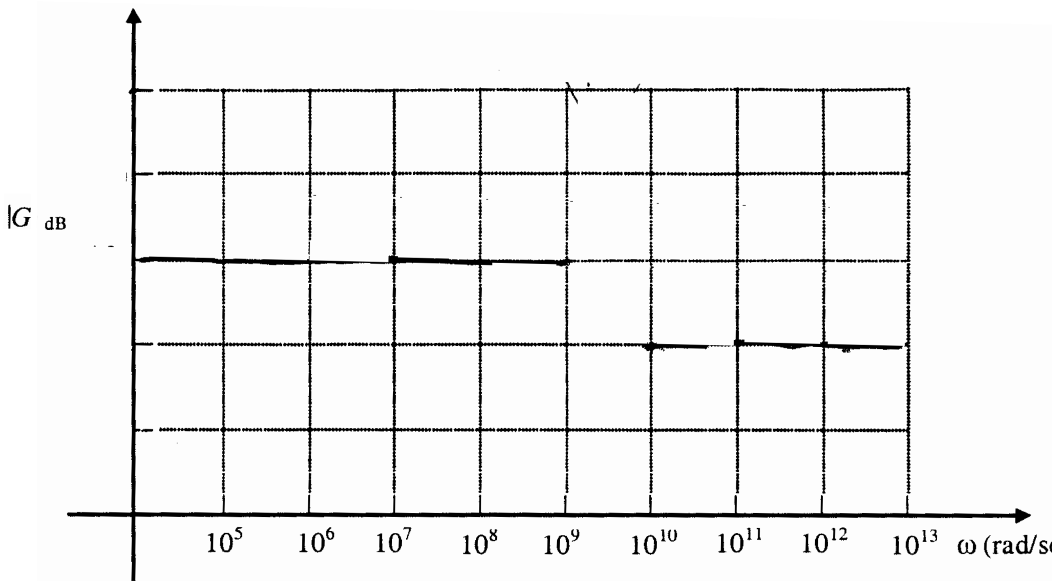
3. Transfer functions:



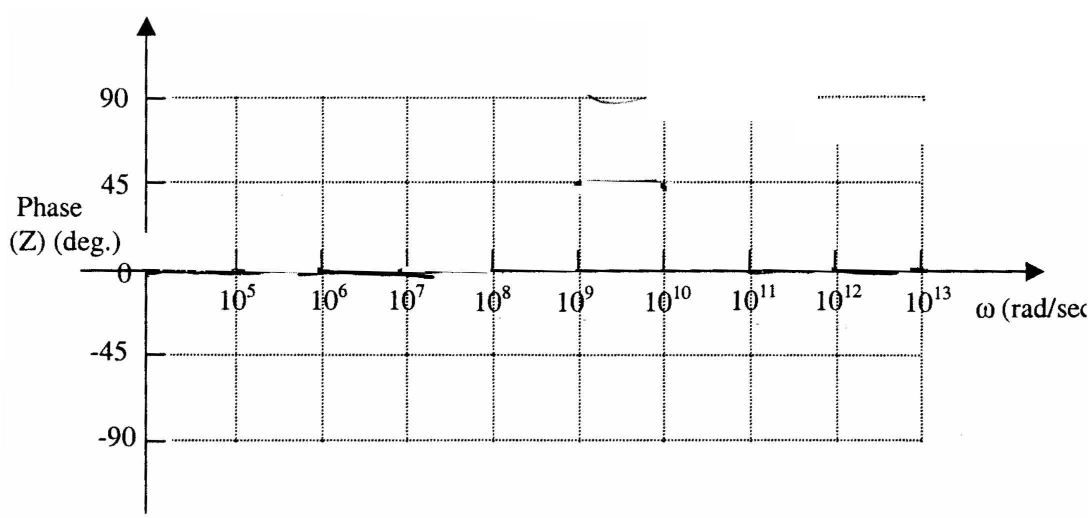
The capacitances $C1 = 1\,\text{pF}$, $C2 = 0.1\,\text{pF}$; resistances $R1 = 100{,}000\Omega$, $R2 = 1000\Omega$.

(a) [10 points] Find an expression for the gain $= Vout / Vin$, where the voltages are phasors, and put it in standard form (gain, poles and zeros) numerator and denominator both factored.

(b) [5 points] Sketch the magnitude Bode plot for the gain G on the graph below using straight-line approximations.



(c) [5 points] Sketch the phase of the impedance Z (units: degrees) on the graph below using straight-line approximations.



(d) [5 points] If the input is Vin(t)=(1volt)sin(10^8 t)+(1 volt)sin(10^7 t), what is the output voltage (not in phasor notation)?

4. MOS transistors

(a) [5 points] In a PMOS device, why is the body typically biased at Vdd rather than ground?

(b) [5 points] If the gate oxide thickness of a PMOS device is doubled, explain why the voltage that you must put on the gate to be at threshold goes down.

(c) [5 points] From the long channel large scale NMOS model given on the attached page, determine the small-signal parameters of a **NMOS** transistor biased in the triode region. What are the most important contributions to the parasitic capacitances for the gate terminal?

(d) [5 points] If you desire to double the small signal transconductance of **a** long channel NMOS transistor in saturation, what parameters could you vary to accomplish that, and by how much would they need to change? Describe at least 3 different ways to double the transconductance.

(e) [5 points] Describe each of the process steps, and draw a mask set for a PMOS transistor made on a p type substrate, and show the cross section through the source, drain, contacts and channel. You don't need to get the names of the masks correct, but label each part of your drawings.

Cutoff

$$\begin{matrix} V_{GS} < V_{TN} \\ V_{GS} > V_{TP} \end{matrix} \Rightarrow I_D = 0$$

Linear (triode)

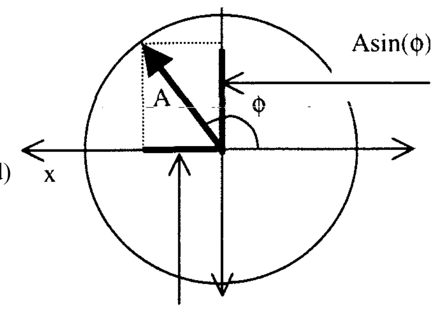
$$\begin{matrix} V_{GS} \geq V_{TN}, \quad V_{DS} < V_{GS} - V_{TN} \\ V_{GS} \leq V_{TP}, \quad V_{DS} > V_{GS} - V_{TP} \end{matrix} \Rightarrow I_D = \mu C_{ox} \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \tfrac{1}{2}V_{DS}^2\right]$$

Saturation

$$\begin{matrix} V_{GS} \geq V_{TN}, \quad V_{DS} \geq V_{GS} - V_{TN} \\ V_{GS} \leq V_{TP}, \quad V_{DS} \leq V_{GS} - V_{TP} \end{matrix} \Rightarrow I_D = \tfrac{1}{2}\mu C_{ox} \frac{W}{L}(V_{GS} - V_T)^2(1 + \lambda V_{DS})$$

Phasor

Definition: a snapshot at time t=0 of counter-clockwise rotating arrow representing a sinusoidal signal.
Magnitude: the length of the phasor; also the peak value of the sinusoidal signal.
$A = \sqrt{[x^2 + y^2]}$
Phase: angle of the phasor with respect to the x-axis in the counter-clockwise direction, at time 0.
$\phi = \tan^{-1}(y/x) = \tan^{-1}(\sin\phi/\cos\phi)$
Note: Be careful when using your calculator to compute $\tan^{-1}$ values! Verify the quadrant!
Angular Frequency: number of radians the arrow rotates through per second. (one full rotation $= 2\pi$ rad)
Notation: ***Time Domain Signal*** ⇨ ***Phasor Notation***
$A\cos(\omega t + \phi)$ → $Ae^{j\phi}$ or $A\angle\phi$



Complex Numbers

$Z = a + bj$	Cartesian/Rectangular Form	a = real, bj = imaginary
$Z = M(\cos\phi + j\sin\phi)$	Polar Form	M = magnitude, ϕ = phase
$Z = Me^{j\phi}$	Exponential Form	M = magnitude, ϕ = phase

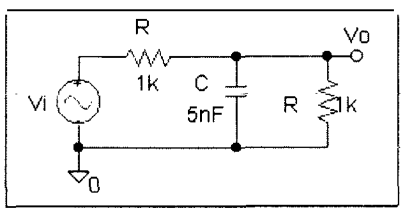
Addition/Subtraction – easier with rectangular form
Multiplication/Division – easier with exponential form

Complex Impedances

$Z_R = R\ [\Omega]$ $Z_C = 1/j\omega C\ [\Omega]$ $Z_L = j\omega L\ [\Omega]$ (All are expressed in Ω, but may be real or complex.)
Capacitors and Inductors can be treated as frequency-dependent resistors for linear circuit analysis using their equivalent impedances. Resistors are treated as usual. In an inductor, voltage leads current, but in a capacitor, current leads voltage. Just remember *ELI* the ICE-man! *E* represents electric potential (voltage) and *I* represents current. *L* represents an inductor and *C* represents a capacitor. (i.e. *E* comes before *I* in *ELI* (L = inductor))

Example

(a) Find the transfer function, V_o/V_i
(b) Determine the DC gain, A_{v0}.
(c) Determine any poles and zeros.
(d) Draw the magnitude and phase Bode plots.



Example

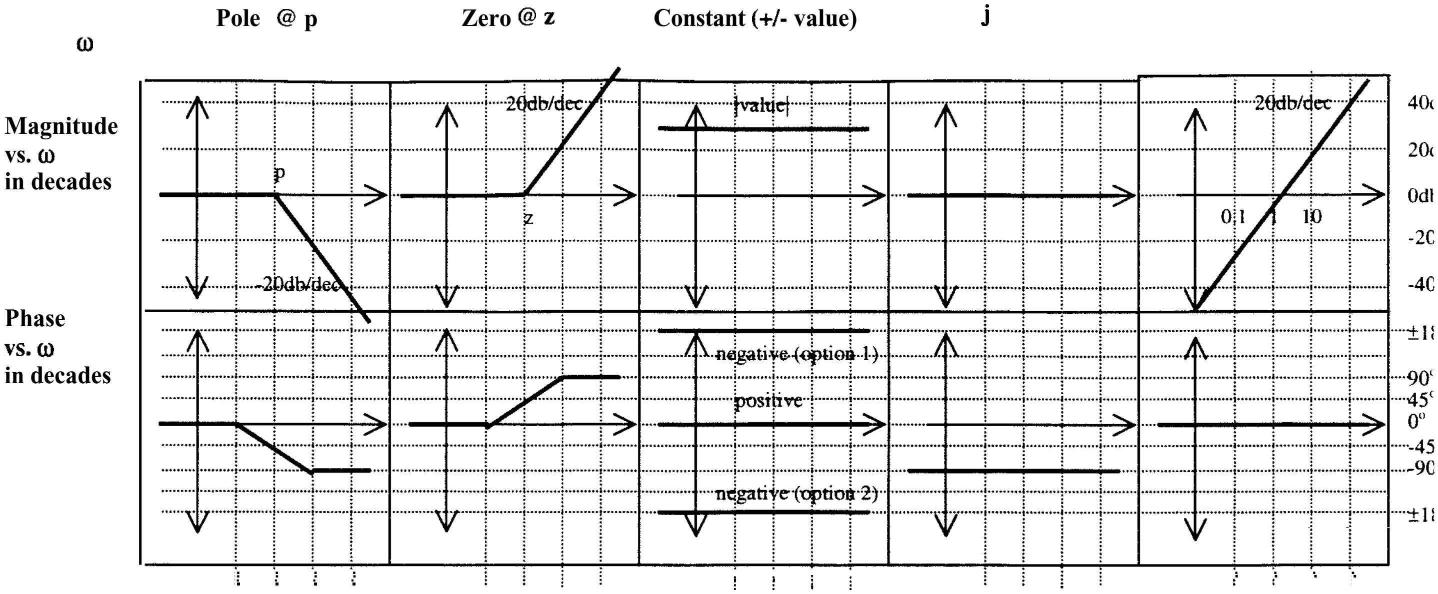
$$H(j\omega) = \frac{-j\omega 5000(10 + j\omega/20)}{(2 + j\omega/20k)(4 + j\omega/200k)}$$

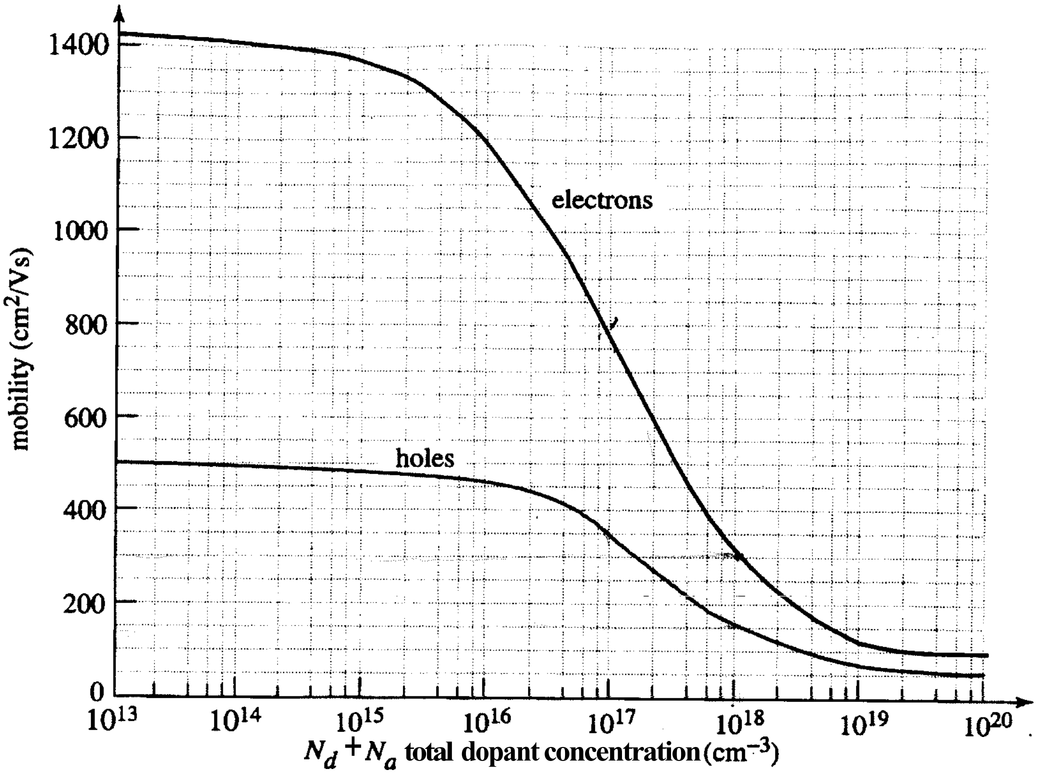
(a) Find A_{v0}, poles, and zeros.
(b) Draw Bode plots.

Bode Plot Basics

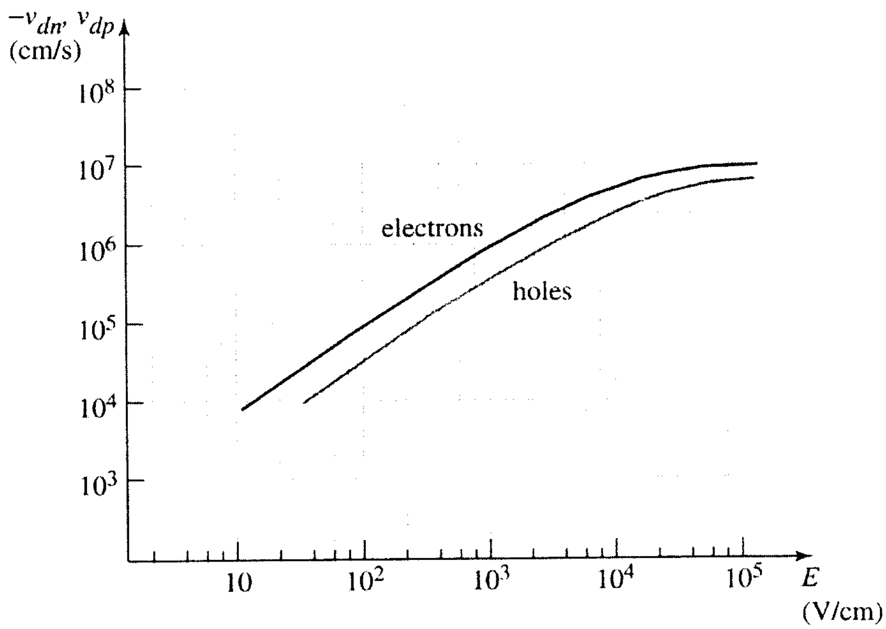
(1) Always draw magnitude plot above and aligned with phase plot.
(2) Use the straight-line approximations to get an idea of what the circuit is doing, but...
(3) Actual transfer function does NOT have sharp comers. At single pole or zero location, there is a 3db difference between actual transfer function magnitude and linear approximation.
(4) Only use transfer function in proper form to pick out poles, zeros, and A_{v0}. See examples above.
(5) Draw complex Bode one multiplier at a time, then add the graphs together. (multiplication in T.F. = Bode addition)

Drawing Guidelines (all lines extend beyond the graphs)





1400
1200
1000
800
600
400
200
0
mobility (cm²/Vs)
electrons
holes
10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
$N_d + N_a$ total dopant concentration (cm⁻³)



$-v_{dn}$, v_{dp}
(cm/s)
10⁸
10⁷
10⁶
10⁵
10⁴
10³
electrons
holes
10 10² 10³ 10⁴ 10⁵
E
(V/cm)