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

EE 105 Midterm I

Spring 2002 Prof. Roger T. Howe March 6, 2002

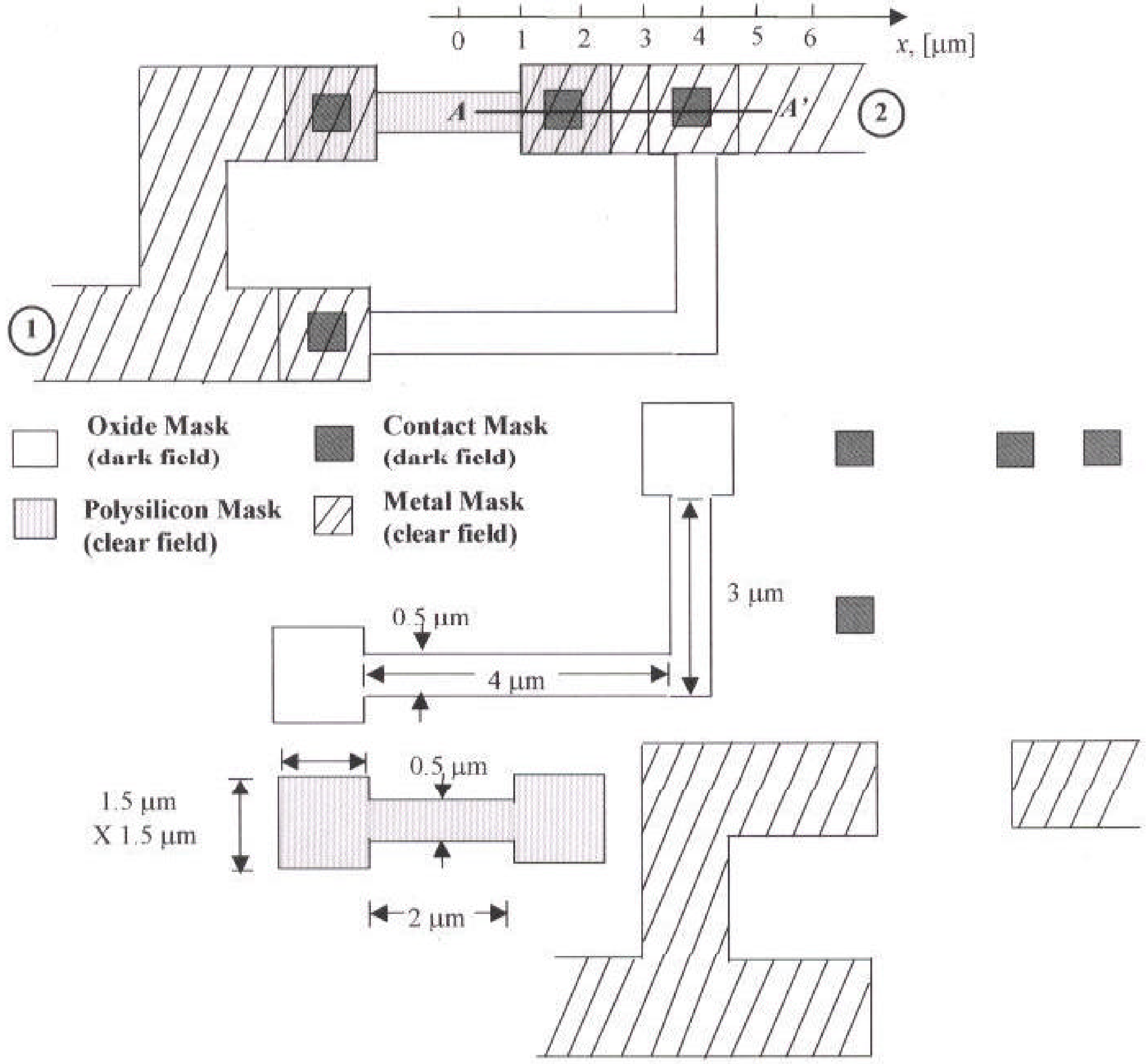
Guidelines

Closed book and notes; one 8.5" x 11" page (both sides) 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	17	
2	17	
3	16	
Total	50	

1. IC resistors [17 points]

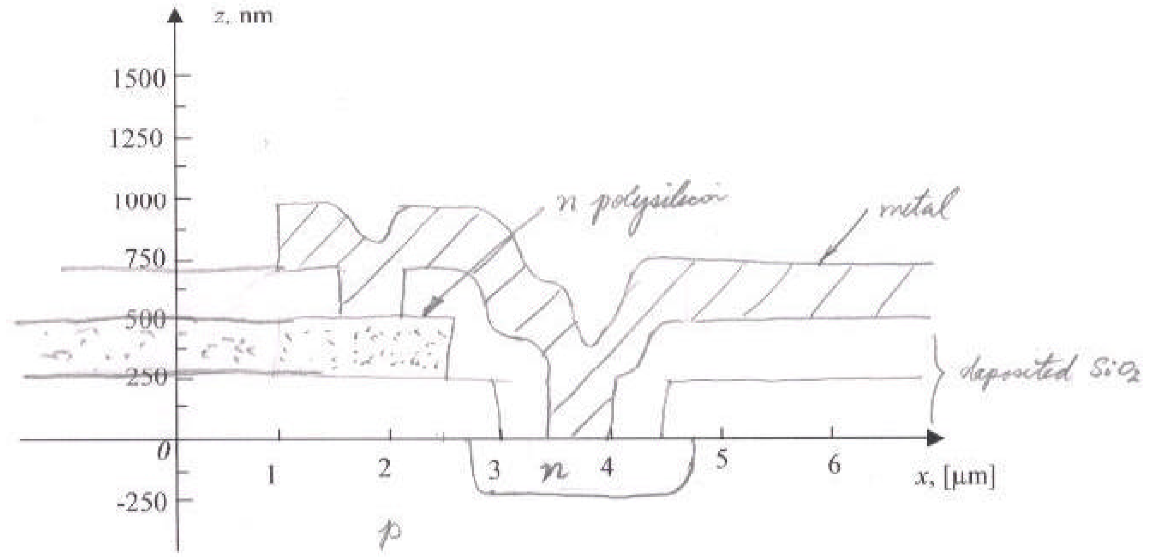


Process Sequence:

1. *Starting material*: p-type silicon wafer with a doping concentration of $1 \times 10^{\overset{17}{16}}$ cm^{-3}
2. Deposit a 250 nm-thick SiO$_2$ layer
3. Deposit a 250 nm-thick layer of n-type polysilicon and pattern using the **Polysilicon Mask** (clear field).
4. Pattern the oxide using the **Oxide Mask** (dark field).
5. Implant phosphorus with dose $Q_d = 5 \times 10^{12}$ cm^{-2} and anneal to form a 250 nm thick phosphorus-doped region.
6. Deposit a 250 nm-thick SiO$_2$ layer and pattern using the **Contact Mask** (dark field).
7. Deposit ~~0.5 µm~~ 250 nm of aluminum and pattern using the **Metal Mask** (clear field).

Given: mobilities for this problem are $\mu_n = 500$ cm^2/(Vs) and $\mu_p = 200$ cm^2/(Vs) for both silicon and polysilicon). The saturation electric field for electrons in polysilicon or silicon is $E_{sat} = 2 \times 10^4$ V/cm and their saturation velocity is $v_{sat} = 10^7$ cm/s. The mobile electron concentration in the polysilicon is $n = 10^{17}$ cm^{-3} at the end of the process. Count the "dogbone" contact areas as 0.65 square each and the corner square as 0.56 squares in finding the resistance.

(a) [5 pts.] Sketch the cross section ***A-A'*** on the graph below **after step** 7. Identify all layers clearly.



(b) [3 pts.] What is the sheet resistance $R_{\square}$ of the 0.25 µm-thick silicon region formed in step 5?

$$R_{\square} = \frac{\rho_n}{t} = \frac{1}{q\underbrace{(N_d - N_a)}_{n}\mu_n t} = \frac{1}{(1.6\times10^{-19})((2-1)\times10^{17})(5\times10^{2})(\frac{1}{4}\times10^{-4})}$$

$$N_d = \frac{Q_d}{t} = \frac{5\times10^{12}\,cm^{-2}}{\frac{1}{4}\times10^{-4}\,cm} = 2\times10^{17}\,cm^{-3}$$

$$= \frac{10^4}{(1.6\times5)/4} = 5000\,\Omega/\square$$

$$\boxed{R_{\square} = 5\,k\Omega/\square.}$$

(c) [3 pts.] What is the maximum current I_{max} in µA resistance through the polysilicon resistor?

$$I_{max} = J_{max}\cdot(\overset{0.5\mu m}{W}\cdot\overset{0.25\mu m}{t})_{poly} = (\overset{1.6\times10^{-19}}{q}\,\underset{10^{17}cm^{-3}}{n}\,\overset{10^{7}cm\,s^{-1}}{v_{max}})(1.25\times10^{-9}cm^{2}) = 2\times10^{-4}A$$

$$\boxed{I_{max} = 200\ \mu A}$$

(d) [4 pts.] Plot the current-voltage curve between terminals 1 and 2 over the range indicated on the graph below.

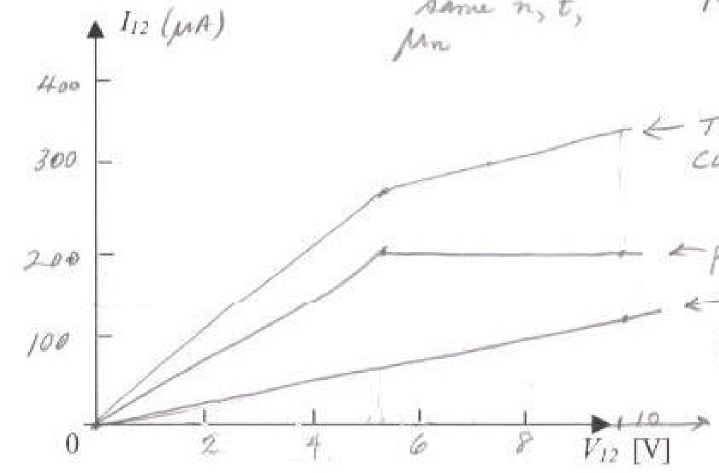
- POLY RESISTOR:

$$V_{max} = (I_{max})\cdot\underbrace{R_{poly}} = (200\mu A)(26.5k\Omega) = 5.3V$$

$$R_{\square poly} = R_{\square n} = 5k\Omega/\square$$

$$N_{\square poly} = (2/0.5) + 2(0.65) = 5.3$$

same n, t, μ_n



$$R_n = (5k\Omega/\square)\,N_{\square n}$$

$$N_{\square n} = \frac{4}{0.5} + \frac{2.5}{0.5} + 0.56 + 2(0.65) = 14.86\ \square$$

$$R_n = 74.3\ k\Omega.$$

(e) [3 pts.] The total voltage between terminals 1 and 2 is:

$$v_{12}(t) = V_{DC} + v_{ac}\cos(\omega t)$$

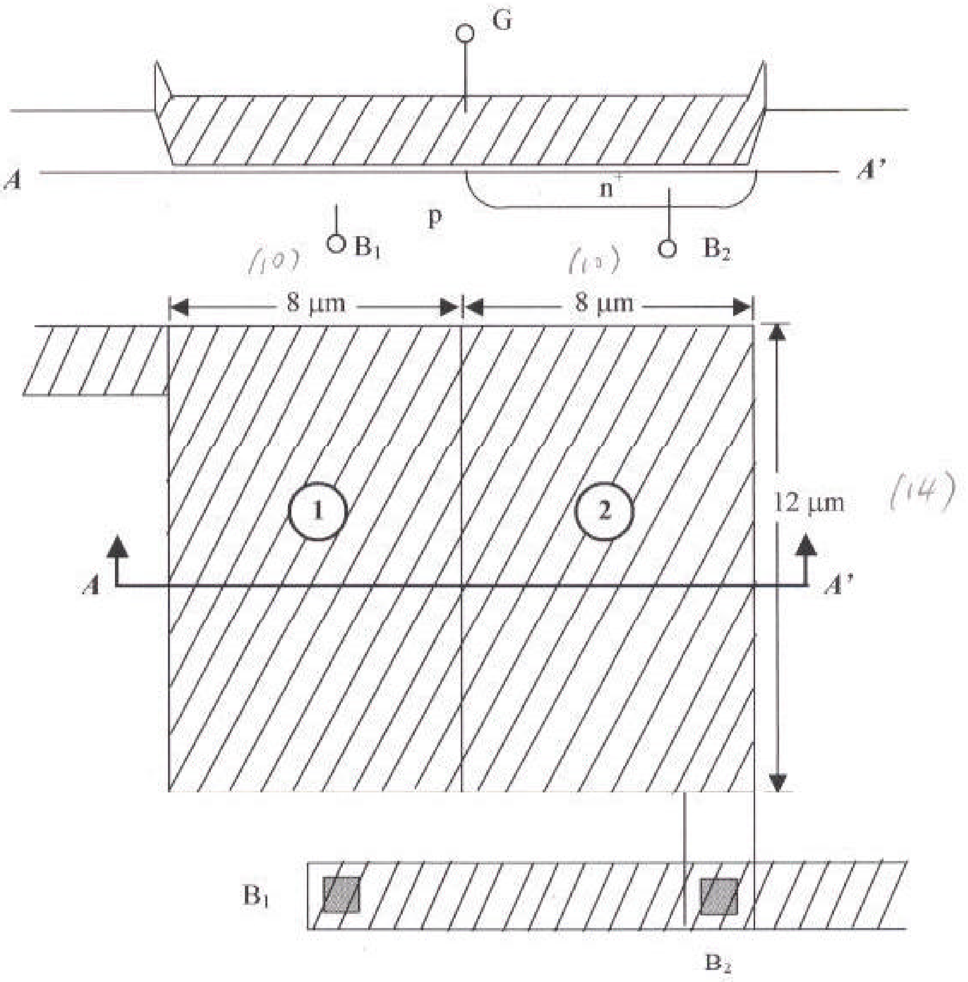
with V_{DC} = ~~2.5~~ 7.5 V and v_{ac} = 5 mV. What is the small-signal component of the current between terminals 1 and 2?

$$r = \left.\frac{\partial v_{12}}{\partial i_{12}}\right|_{V_{DC}} = R_n = 74.3k\Omega$$

$$i_{12} = v_{ac}/R_n = \frac{5mV}{74.3k\Omega} = 67nA$$

$$\boxed{i_{12}(t) = (67\ nA)\cos\omega t}$$

2. MOS charge-storage element [17 pts.]



The MOS structure shown in cross section and top view above has a metal gate and two bottom electrodes, B_1 (p substrate) and B_2 (n^+ layer). The bottom electrodes are contacted by a metal line and shorted together, as indicated on the top view. The oxide thickness is t_{ox} = ~~10~~ nm for the MOS structure. $\epsilon_{ox} = 3.45 \times 10^{-13}$ F/cm
11.5

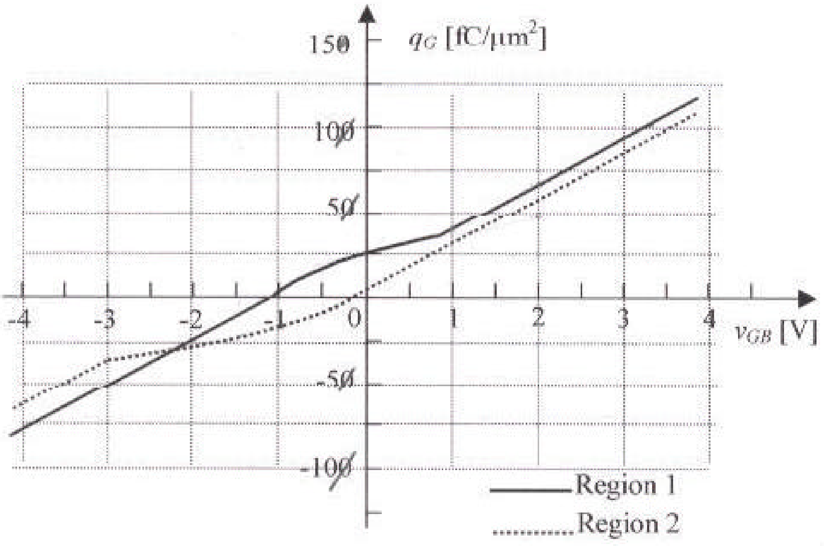
In region 1, the p-type substrate is the bottom electrode and the MOS parameters are:

V_{FB} = -1.2 V, V_{Tn} = 0.8 V

In region 2, the n^+ layer is the bottom electrode and the MOS parameters are:

V_{FB} = -0.2 V, V_{Tp} = -3 V

The charge storage curves for the two regions are provided on the graphs below of gate charge per unit area versus the gate-bottom electrode potential, v_{GB}. Since $B_1 = B_2$, we use "B" to represent the potential of the bottom electrode for each region.



(a) [4 pts.] For $v_{GB} = 1$ V, find the total charge on the gate (units: femtoCoulombs = 10^{-15} C).

$$\left.\begin{array}{l} q_{G_1} \approx 4\ fC/\mu m^2 \\ q_{G_2} \approx 3\ fC/\mu m^2 \end{array}\right\} \qquad q_{G_{TOT}} = q_{G_1} A_1 + q_{G_2} A_2$$

$$= (4\ fC/\mu m^2)(8 \times 12\ \mu m^2) + (3\ fC/\mu m^2)(8 \times 12\ \mu m^2)$$

$$(140\ \mu m^2) \qquad\qquad (140\ \mu m^2)$$

$$\boxed{q_{G_{TOT}} = 672\ fC}$$

(980 fC)

(b) [4 pts.] For $v_{GB} = -1.5$ V, identify the substrate charge in regions 1 and 2 by circling the correct description(s). Note: the correct answer may have more than one description circled.

Region 1. ionized acceptors [✓ accumulated holes] inversion-layer electrons

Region 2. [✓ ionized donors] accumulated electrons inversion-layer holes

(c) [4 pts.] For $v_{GB} = +1.5$ V, identify the substrate charge in regions 1 and 2 by circling the correct description(s). Note: the correct answer may have more than one description circled.

Region 1. [✓ ionized acceptors] accumulated holes [✓ inversion-layer electrons]

Region 2. ionized donors [✓ accumulated electrons] inversion-layer holes

(d) [3 pts.] If we apply a voltage $v_{GB}(t) = 0\text{ V} + v_{gb}\cos(\omega t)$, where v_{gb}=5 mV and $\omega = 2\pi(10^6)$ rad/s, estimate the current $i_{gb}(t)$ into the gate terminal in nA from the charge-storage curves.

acc. $C_{gb_2} = C_{ox} A_2 = \left[\dfrac{3.45\times10^{-13}\text{ F/cm}}{1.15\times10^{-6}\text{ cm}}\right]\left[8\times12\times10^{-8}\text{ cm}^2\right] = 288\text{ fF}$

(140)

depletion $C_{gb_1} = \left.\dfrac{\partial q_{G_1}}{\partial v_{GB}}\right|_{V_{GB}=0} A_1 \approx \underbrace{\left(\dfrac{2.5\text{ fC}/\mu\text{m}^2}{2\text{ V}}\right)}_{\text{slope}}\left(96\,\mu\text{m}^2\right) = 120\text{ fF}$

(140)

$\Big\}\ C_{gb} = 408\text{ fF.}$

$i_{gb} = -\left[2\pi\,(10^6\,\text{s}^{-1})(5\text{ mV})(408\text{ fF})\right]\sin\omega t = (-12.8\text{ nA})\sin\omega t$

(595) (-18.7)

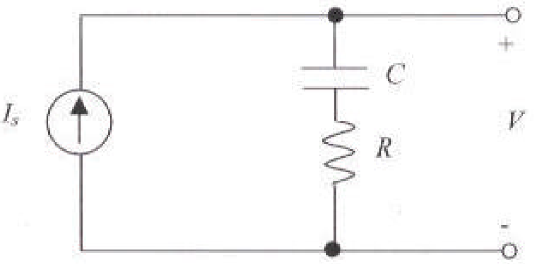
(e) [2 pts.] The maximum capacitance of the MOS structure is C_{max}. If the DC component of v_{GB} is 1.5 V, what is the maximum amplitude of its small-signal component v_{gb} for which the current remains exactly proportional to C_{max}.

$v_{GB} = 1.5\text{ V} + v_{gb}\cos\omega t$

$v_{GB\,min} = 0.8\text{ V} = V_{Tn}$ for $\dfrac{\partial q_{G_1}}{\partial v_{GB}} = C_{ox} A_1 \Rightarrow C = C_{max}$

So $\boxed{v_{gb} \le 700\text{ mV}}$

3. Impedance measurements [16 pts.]



The capacitance $C = 1$ pF and the resistance $R = 1000\ \Omega$.

(a) [4 pts.] Find an expression for the impedance $Z = V / I_s$. Your result should contain the term $(1 + j\,\omega\tau)$.

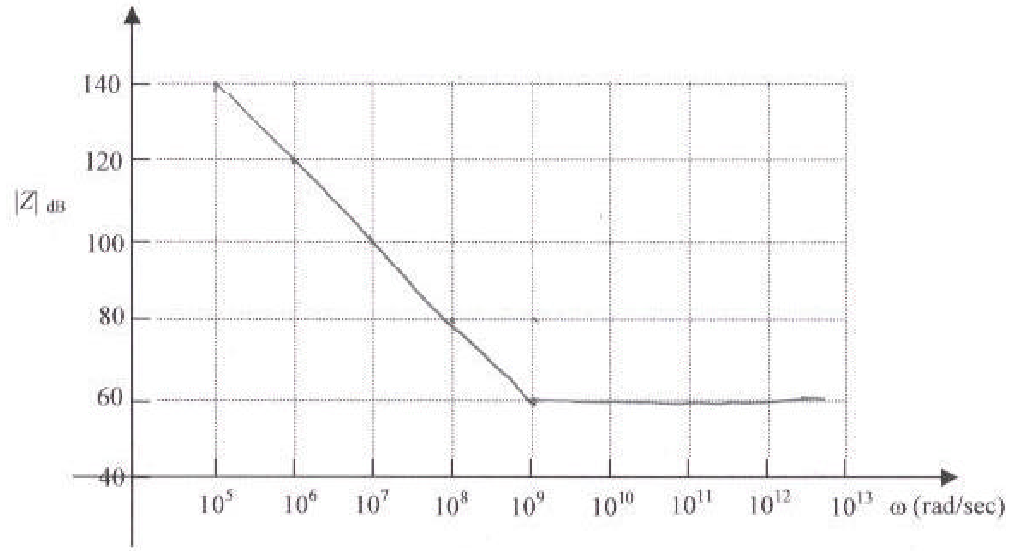
$$Z = \frac{1}{j\omega C} + R = \left(\frac{1}{j\omega C}\right)(1 + j\omega RC)$$

$$= \left(\frac{R}{j\omega\tau}\right)(1 + j\omega\tau) = R\left\{\frac{1 + j\omega\tau}{j\omega\tau}\right\}$$

$\tau = 10^{-9}$ s

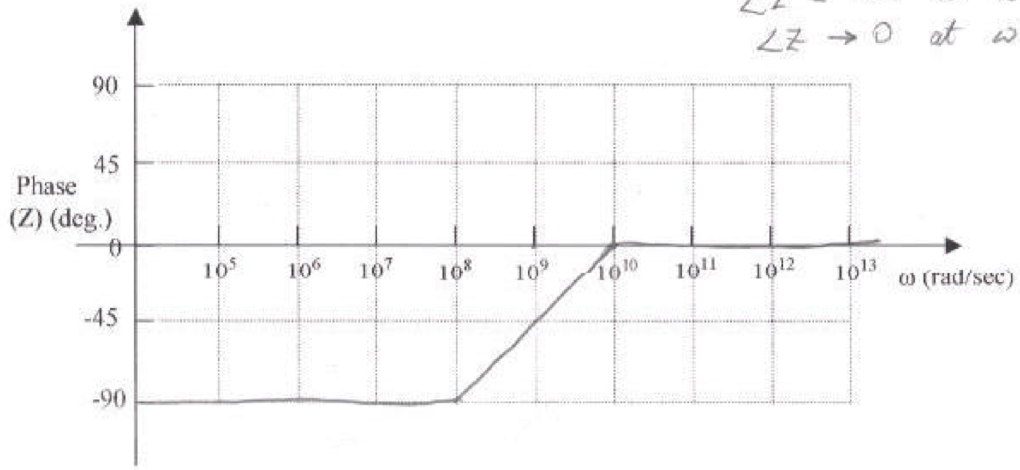
$R = 1\,k\Omega$

(b) [4 pts.] Sketch the magnitude Bode plot for the impedance Z (units: $20 \log_{10}(\Omega)$) on the graph below using straight-line approximations.

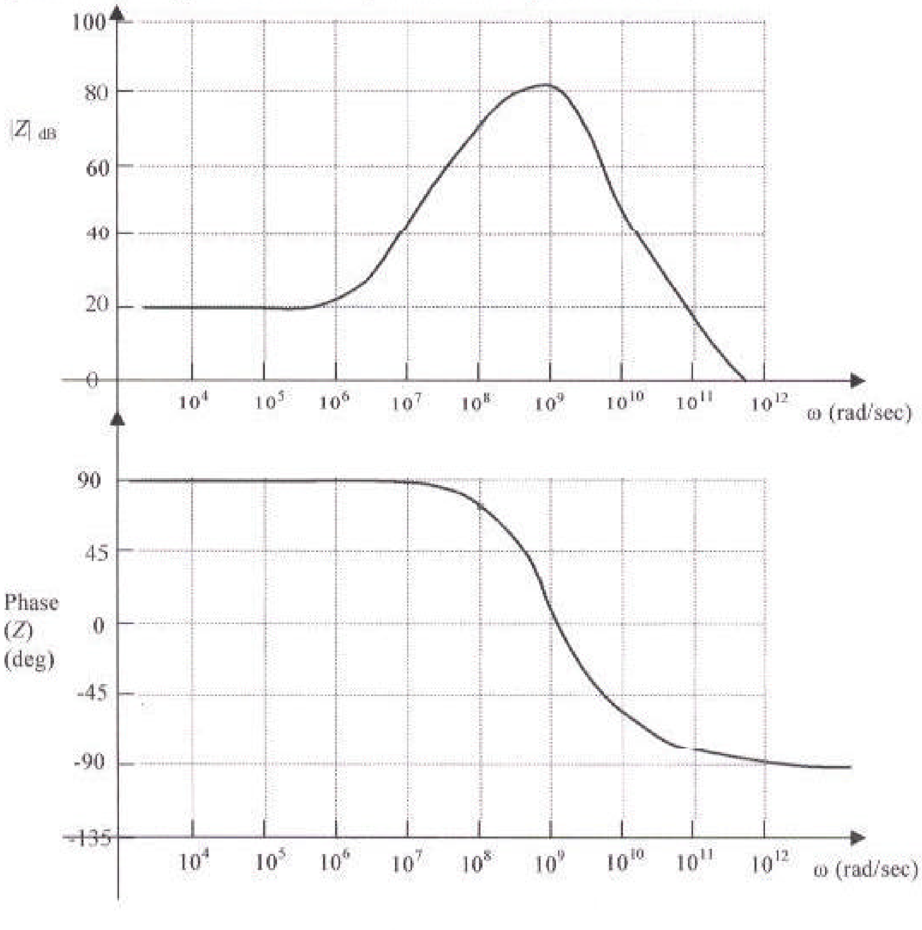


(c) [4 pts.] Sketch the phase of the impedance Z (units: degrees) on the graph below using straight-line approximations.

$\angle Z = -90^\circ$ at $\omega << 1/\tau = 10^9$
$\angle Z \rightarrow 0$ at $\omega >> 1/\tau$



(d) [4 pts.] You hook up another two-terminal circuit and measure its impedance. The Bode plots of the magnitude and the phase of Z are plotted below.



If a phasor current $I_s = (2.5\mu A)e^{j(0°)}$ at $\omega = 10^8\ \text{rad}\,\text{s}^{-1}$ what is the voltage waveform $v(t)$ based on the information in the Bode plots?

$$|Z| = 3.16\,k\Omega$$

$$\left.\begin{array}{l} |Z|_{dB} = 70\,dB \\ \angle Z = 70° \end{array}\right\} \text{ at } \omega = 10^8\ \text{rads}^{-1}$$

$$V = I_s Z = 7.9\,mV\,e^{j[70°]}$$

$$\boxed{v(t) = (7.9\,mV)\cos(10^8 t + 70°)}$$