NATIONAL EXAMS
MAY 2009

Phys-A5: Semiconductor Devices & Circuits

3 hours duration

NOTES:

1. If doubt exits as to the interpretation of any question, the candidate must submit with the answer paper, a clear statement of any assumption made.

2. Candidates may use one of two calculators, the Casio or Sharp approved models.

3. This is a CLOSED BOOK EXAM.
   Useful constants and equations have been annexed to the exam paper.

4. Any FIVE (5) questions constitute a complete exam paper.
   The first five questions as they appear in the answer book will be marked.

5. When answering questions, candidates must clearly indicate units for all parameters used or computed.

Marking scheme

Questions	*Marks*				
1	(a) 2	(b) 4	(c) 7	(d) 7	
2	(a) 12	(b) 8			
3	(a) 3	(b) 4	(c) 4	(d) 4	(e) 5
4	(a) 4	(b) 4	(c) 12		
5	(a) 4	(b) 4	(c) 12		
6	(a) 4	(b) 4	(c) 8	(d) 4	
7	(a) 10	(b) 10			

1. An intrinsic semiconductor operating at a temperature of T = 300 °K has the following properties:

$n_i = 2\times10^{10}/cm^3$
$\mu_n = \mu_p = 1000\ cm^2/V\text{-}s$
$N_c = N_v = 10^{19}/cm^3$
$\sigma_i = 4\times10^{-6}/\Omega\text{-}cm$

2 pts (a) Find the resistivity of this semiconductor at T = 300 °K.

4 pts (b) Find the band gap E_g of this semiconductor at T = 300 °K.

7 pts (c) Assuming that E_g, N_c and N_v do not change with temperature, evaluate the conductivity of this semiconductor at T = 600 °K.

7 pts (d) If the semiconductor is doped with $N_d = 6\times10^{15}/cm^3$ donors and $N_a = 2\times10^{15}/cm^3$ acceptors, find the difference (in *eV*) between the Fermi level and E_i at T = 300 °K.

2. An abrupt n^+-p junction with a long p-region has the following properties:

$n_i = 10^{10}/cm^3$
$N_a = 10^{16}/cm^3$
$D_p = 13\ cm^2/s$
$\mu_n = 1000\ cm^2/V\text{-}s$
$\tau_n = 2\mu s$

The junction is operating at a temperature of T = 300 °K with a forward bias of 0.7 V.

12 pts (a) If the junction has a constant cross section area $A = 10^{-3}\ cm^2$, calculate the current flowing through this device.

8 pts (b) What is the value of the electrical field in the p-region far from the junction?

3. The magnitude Bode plot of the transfer function F(s) of an active filter is shown in Figure P3.

3 pts (a) Specify if this transfer function is of type *low-pass* or *high-pass* and briefly explain your answer.

4 pts (b) What is the *exact* value (in dB) of the magnitude of F(s) if the input of the filter is a DC signal?

4 pts (c) What is the *approximate* peak amplitude of the output signal of the filter if the input of the filter is a sinusoidal signal of peak amplitude of 0.5 V and frequency $\omega = 25{,}000$ rad/s?

4 pts (d) Find an *exact* algebraic expression for the transfer function F(s) of this filter.

5 pts (e) Find the *exact* value (in dB) of the magnitude of F(s) at a frequency of $\omega = 25{,}000$ rad/s.

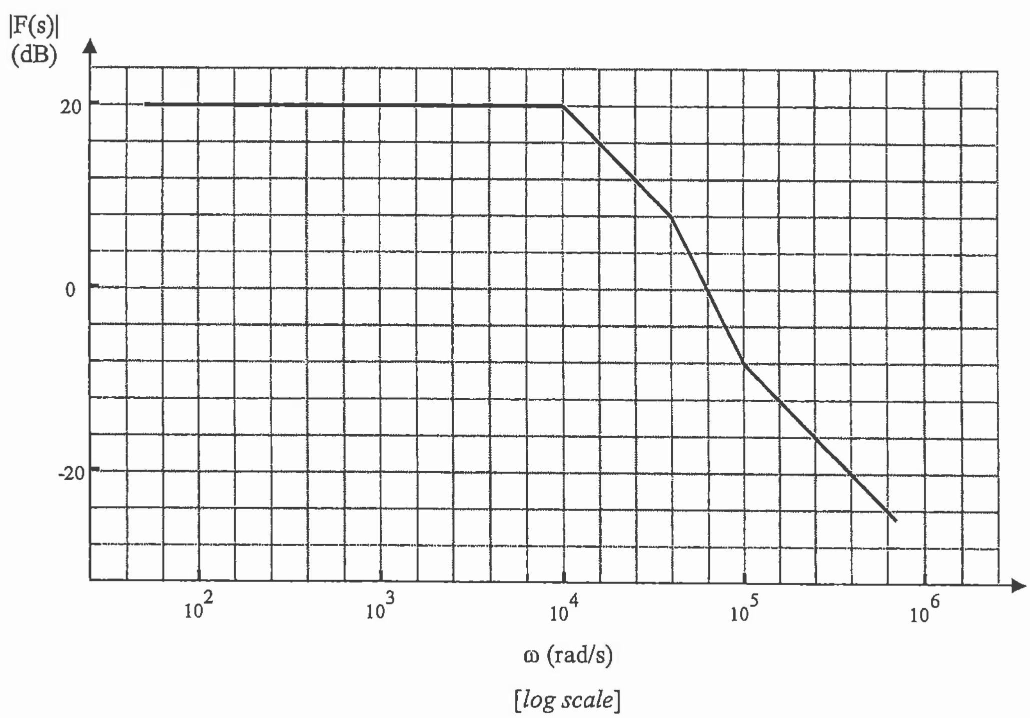


Figure P3

4. The I_C *vs* V_{CE} characteristics of a BJT used in a small signal common emitter amplifier circuit are shown in Figure P4. The chosen Q point and DC load line are also shown. To maximize power transfer to a load of R_L = 1 kΩ the amplifier must have an output resistance of $R_o = R_L$. To limit power losses in the input bias circuit, R_2 is set such that its DC current is not to exceed $10I_B$.

4 pts (a) Assuming that V_T = 26 mV, show that, at the Q point
$\beta_{DC} = 130$, $g_m = 250$ mS, $r_\pi = 520\ \Omega$ and $r_o \approx 52$ KΩ

4 pts (b) What will be the sign and magnitude of the midband voltage gain of this amplifier? (Assume capacitors have zero impedance at midband.)

12 pts (c) Determine the values of resistors R_C, R_E, R_2, and R_1 to bias the transistor at the chosen Q point and to meet all other specifications of the amplifier. Assume that $V_{BE(on)}$ = 0.7 V.

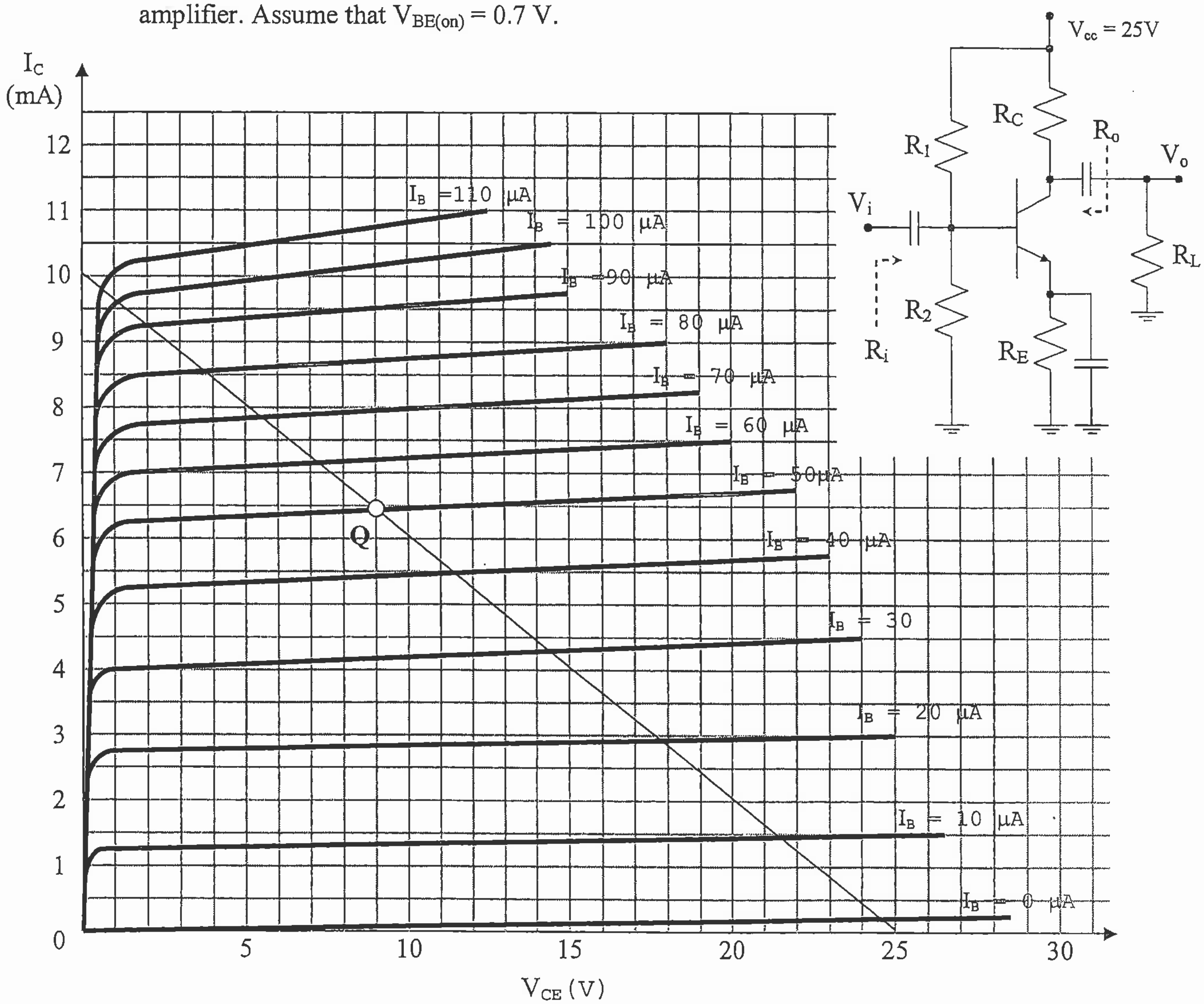


Figure P4

5. The two circuits shown in Figure P5 are designed to provide the same gain and the same input resistance R_{in}.

4 pts (a) Using the circuit on the left, show that $R_{in} = R$.

4 pts (b) If R_{in} must be high, what is the advantage of using the circuit on the right?

12 pts (c) What value must the ratio R/r be for the two circuits to have the same gain $G \equiv V_o/V_i$?

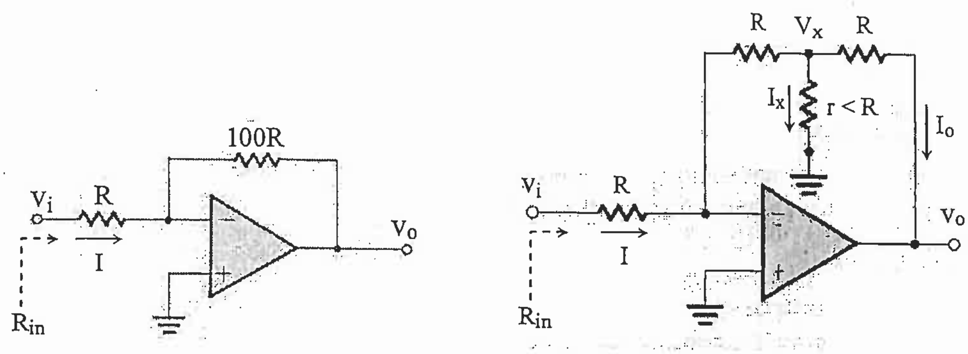


Figure P5

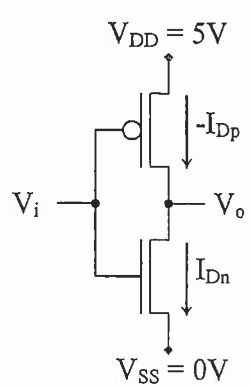
6. Figure P6 shows a CMOS inverter and key values on its voltage transfer characteristic.

4 pts (a) Calculate noise margins of this logic gate.

4 pts (b) What is the approximate gain of the circuit?

8 pts (c) If $V_{tn} = -V_{tp} = 1$ V and $k_n = 2k_p$, calculate the exact value of V_i when $V_i = V_o$.

4 pts (d) Explain how the PMOS transistor can be modified to shift the curve so that its goes through the point $V_i = V_o = 2.5$ V in order to provide more symmetry.



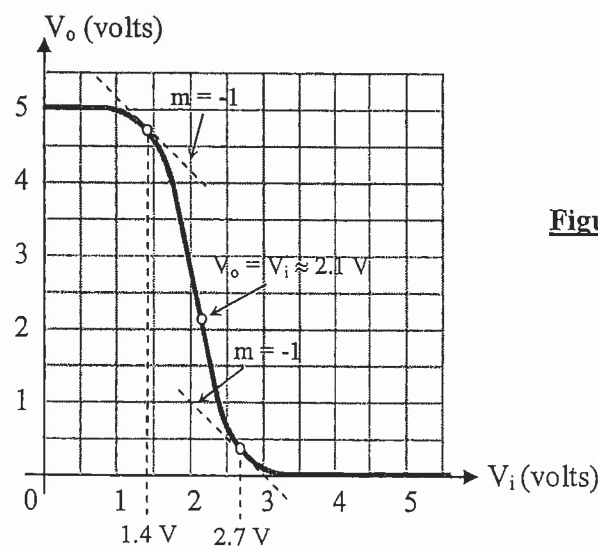


Figure P6

7. Figure P7 shows the basic diagram of a precision bridge rectifier for instrumentation applications. The OP amp is assumed to be ideal. The meter M has a coil resistance of r = 50 Ω and provides a full-scale deflection when the average current through it is1 mA.

10 pts (a) Find the value of R to provide a full-scale reading when the input voltage is a sine wave of 5 V rms.

10 pts (b) Assuming the diodes have a constant 0.7 V drop when conducting, what is the maximum positive voltage that can appear at the output of the OP amp?

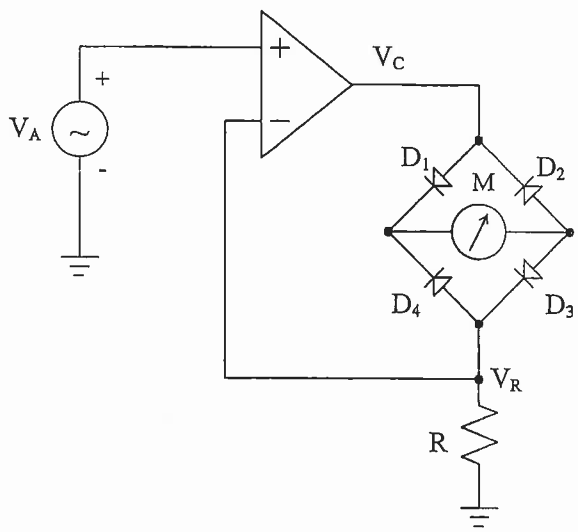


Figure P7

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ANNEX A

USEFUL CONSTANTS AND EQUATIONS

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(1) $1\,\mathring{A} = 10^{-10}\,m = 10^{-8}\,cm = 10^{-4}\,\mu m$

(2) $q = 1.6x10^{-19}\,C$

(3) $k = 1.38 \times 10^{-23}\,J/°K = 8.62 \times 10^{-5}\,eV/°K$ [At T = 300°K, $kT/q \approx 26$ mV kT = 0.026 eV]

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(4) For silicon (Si) at T = 300 °K: $n_i = 1.5x10^{10}/cm^3$

(5) $\varepsilon_{Si} = 1.04x10^{-12}$ F/cm

(6) $\varepsilon_{SiO2} = 0.345x10^{-12}$ F/cm [farad: 1 F = 1 C/V] [siemens: 1 S = 1 mA/V]

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(7) $n_o + N_a = p_o + N_d$

(8) $n_o p_o = n_i^2$

(9) $n_o = n_i e^{(E_F - E_i)/kT}$

(10) $p_o = n_i e^{(E_i - E_F)/kT}$

(11) $n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT}$

(12) $V_o = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$

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(13) $\sigma = q(n_o \mu_n + p_o \mu_p)$

(14) $\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = \frac{kT}{q}$ $L_n = \sqrt{D_n \tau_n}$ $L_p = \sqrt{D_p \tau_p}$

(15) $n_n p_n = n_i^2 = n_p p_p$

(16) $I = I_o(e^{\frac{qV}{kT}} - 1) = qA\left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p\right)(e^{\frac{qV}{kT}} - 1)$

(17) $J = \frac{I}{A} = \sigma \mathcal{E}$

(18) $R = \frac{L}{\sigma A}$

(19) $V_{average} = \frac{1}{T}\int_0^T V(t)\,dt$ [for a half-wave rectified sinewave, $V_{average} = V_{peak}/\pi$]

[for a full-wave rectified sinewave, $V_{average} = 2V_{peak}/\pi$]

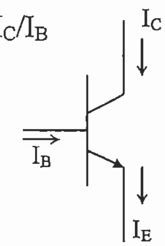
BJT relationships and model

(20) $I_C = \beta I_B$ where $\beta = I_C/I_B$

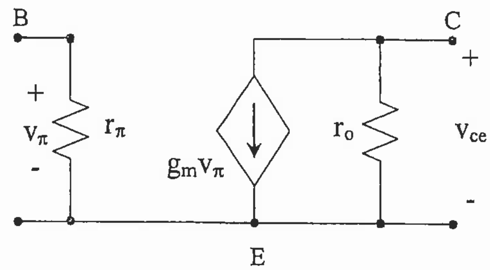
(21) $I_E = I_B + I_C$

(22) $g_m = I_C/V_T$

(23) $r_\pi = V_T/I_B$



Small signal BJT model



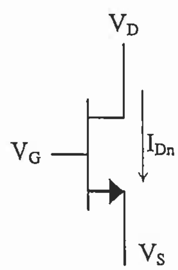
NMOS and PMOS relationships

(24) $I_{Dn} = (k_n/2)\,(V_{GSn} - V_{tn})^2$ when $V_{DSn} > V_{GSn} - V_{tn}$

(25) $I_{Dn} = (k_n/2)\,[2(V_{GSn} - V_t)(V_{DSn}) - (V_{DSn})^2]$ when $V_{DSn} < V_{GSn} - V_{tn}$

(26) $I_{Dp} = -(k_p/2)\,(V_{GSp} - V_{tp})^2$ when $V_{DSp} < V_{GSp} - V_{tp}$

(27) $I_{Dp} = -(k_p/2)\,[2(V_{GSp} - V_{tp})(V_{DSp}) - (V_{DSp})^2]$ when $V_{DSp} > V_{GSp} - V_{tp}$



Small signal FET model