NATIONAL EXAMS
MAY 2014

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) of the SEVEN (7)** 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) 5	(b) 5	(c) 6	(d) 4		
2	(a) 3	(b) 4	(c) 8	(d) 5		
3	(a) 6	(b) 3	(c) 4	(d) 7		
4	(a) 4	(b) 16				
5	(a) 5	(b) 5	(c) 5	(d) 5		
6	(a) 3	(b) 1	(c) 1	(d) 5	(e) 5	(f) 5
7	(a) 6	(b) 9	(c) 5			

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1. Measurements conducted at a temperature T = 300 °K on a sample of pure silicon (Si) show that this semiconductor material has a diamond lattice constant a = 5.43 Å, 8 atoms per cell, an atomic weight of 28.1, and a band gap of 1.12 eV.

5 pts (a) Find the density of pure Si in g/cm^3.

5 pts (b) What is the probability for an electron to occupy an energy state situated halfway between the Fermi level and the edge of the conduction band?

6 pts (c) If the Si is doped with 10^{17} acceptor atoms/cm^3, what is the equilibrium electron concentration in the sample?

4 pts (d) If the Si is doped with donor atoms, what happens to the Fermi level of the sample?

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2. A diode is fabricated by using an abrupt silicon *p-n* junction formed by merging p-type and n-type semiconductors of constant cross section A = 10^{-4} cm^2. The properties of the semiconductors for a temperature of T = 300 °K are shown in Table T2 and the I-V characteristic of the diode is shown in Figure P2.

3 pts (a) An engineer decides to use a voltmeter to measure the contact potential of the diode. What value would the voltmeter show?

4 pts (b) Briefly explain why the I-V characteristic is exponential for V > 0 V ?

8 pts (c) What is the current in the diode when V = -2 V and -4 V ?

5 pts (d) What is the current in the diode when V = +0.38 V and +0.76 V ?

Table T2 - Properties of junction semiconductors at T = 300 °K

p type	*n type*
$N_a = 10^{17}$ cm^{-3}	$N_d = 10^{15}$ cm^{-3}
τ_n = 0.1 µs	τ_p = 10 µs
μ_p = 200 cm^2/(V-s)	μ_n = 1300 cm^2/(V-s)
μ_n = 700 cm^2/(V-s)	μ_p = 450 cm^2/(V-s)

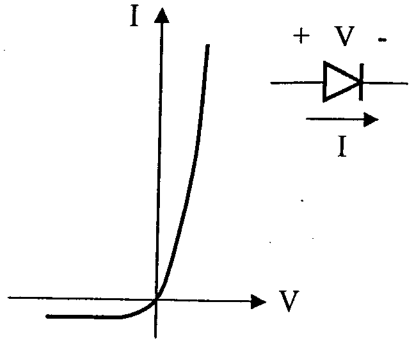

Figure P2

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3. A useful filter circuit shown in Figure P3.

6 pts (a) Show that the filter transfer function is given by

$$F(s) = \frac{V_o}{V_i} = \frac{R_2}{R_1}\frac{s-\omega_o}{s+\omega_o}$$

where $\omega_o = 1/RC$.

3 pts (b) What is the order of this filter? Briefly explain your answer.

4 pts (c) Show that the magnitude of *F(s)* does not change with frequency and express the value of this magnitude in dB.

7 pts (d) Select a value for capacitor C (in μF) to obtain a phase shift of 135° at a frequency of 415 Hz.

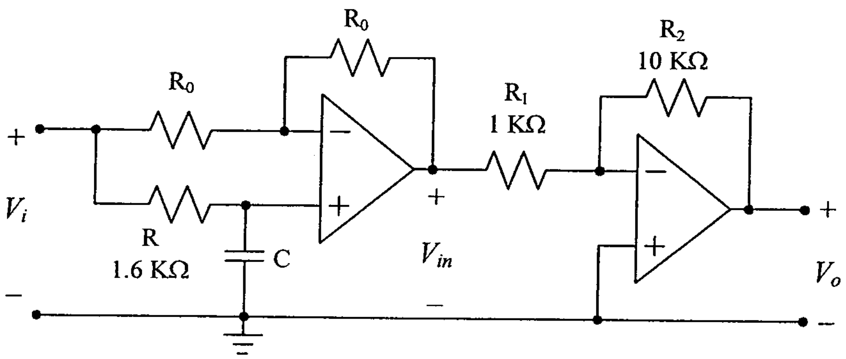

Figure P3

4. For the circuit shown in Figure P4, the two OP amps are used in a negative feedback configuration.

4 pts (a) What is the value of voltage V_A ?

16 pts (b) Find the value of voltage V_o.

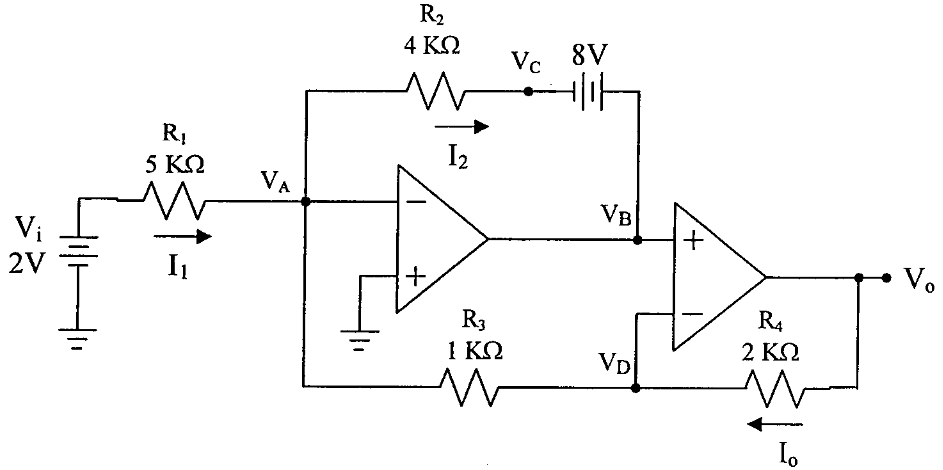

Figure P4

5. A small signal amplifier circuit using a BJT is shown in Figure P5. The small signal characteristics of the transistor are shown in Table T5. The circuit is used to drive a load $R_L = 1.5$ KΩ.

5 pts (a) Determine the value of R_C to obtain a gain of -150.

5 pts (b) Determine the value of R_E to bias the BJT at $V_{CEQ} = 12$ V and $I_{CQ} = 6.5$ mA

5 pts (c) Determine the values of resistors R_1 and R_2 to complete the biasing of the BJT with the constraint that the DC current in R_2 should be at most 5 I_{BQ}.

5 pts (d) With the values of bias resistors found in the previous steps, evaluate the input resistance R_i and the output resistance R_o of the amplifier.

Table T5 – BJT parameters

$V_{BE(on)}$	0.5 V
β_{DC}	130
g_m	250 mS
r_π	520 Ω
r_o	80 KΩ

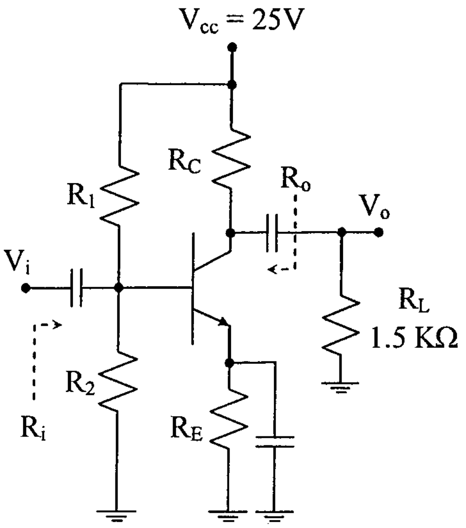

Figure P5

6. Figure P6a, Figure P6b and Figure P6c show three types of analog-to-digital converters (ADCs). For all three ADCs, the reference voltage is $V_{ref} = 3.2$ V.

3 pts (a) Name the types of the three ADCs.

1 pts (b) List one main advantage for each of the three types of ADCs.

1 pts (c) List one main disadvantage (limitation) for each of the three types of ADCs.

5 pts (d) For the ADC of Figure P6a, if $V_A = 2.18$ V, determine the 5-bit value of the digital output.

5 pts (e) The ADC of Figure P6b is using a clock of frequency $f = 1$ MHz to convert an analog input in the range $-3\text{V} \leq V_A \leq 0$.
How long does take to convert an analog input value of $V_A = -2.4$ V ?

5 pts (f) What is the full-scale voltage of the ADC shown in Figure P6c ?

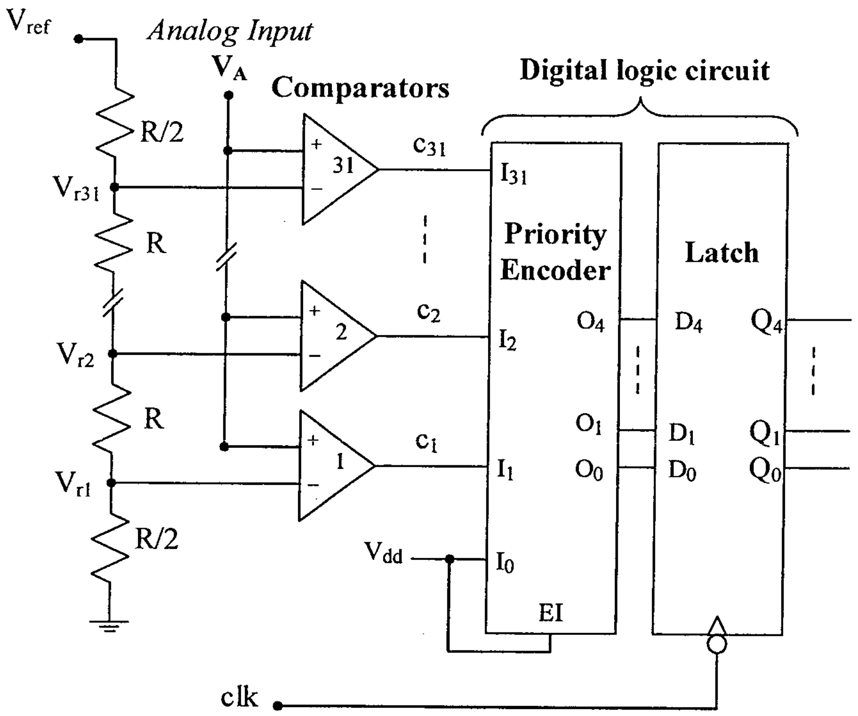

Figure P6a

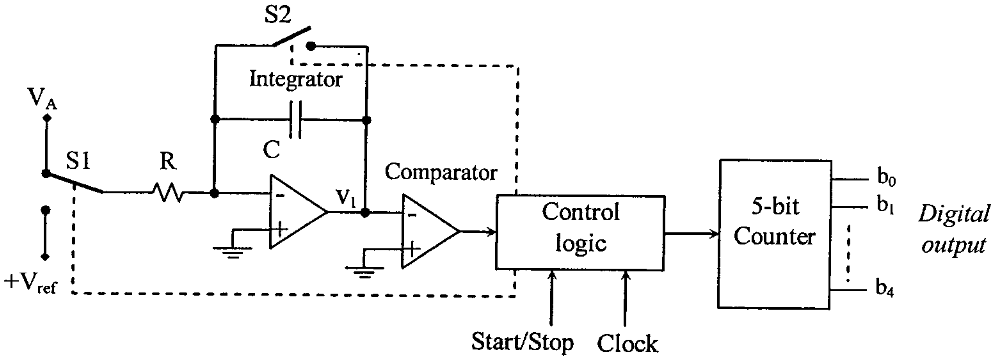

Figure P6b

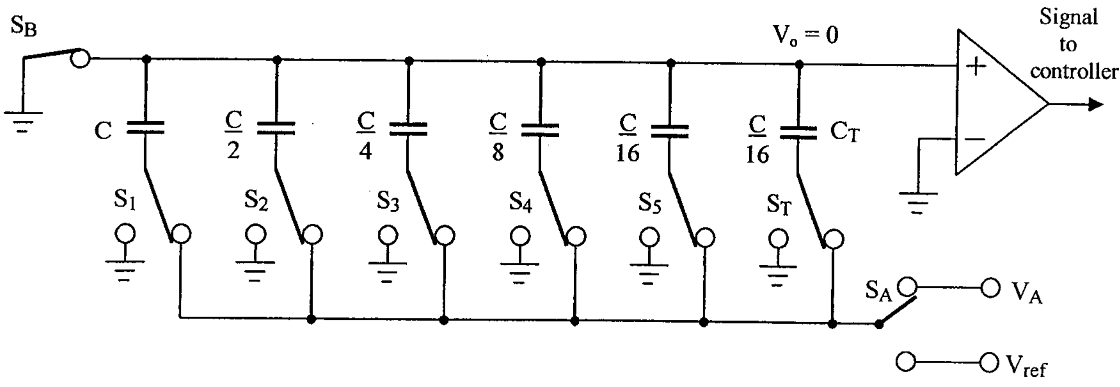

Figure P6c

7. An instrumentation apparatus makes use of the circuit shown in Figure P7a to detect the zero crossings of a noisy signal. The circuit prevents false zero crossings detection (see Figure P7b) since it has an hysteresis zone centered around the 0 V level.

6 pts (a) Sketch the transfer characteristic $V_o(V_i)$ of the circuit shown in Figure P7a. Clearly indicate the levels of the output signal V_o and where V_{TH} and V_{TL} are situated on the V_i axis with respect to the origin.

9 pts (b) Find suitable values for resistors R_1 and R_2 in the range of 1 KΩ to 200 KΩ to set the switching thresholds at $V_{TL} = -V_{TH} = 0.25$ V. The resistors must be as large as possible.

5 pts (c) The circuit of Figure P7c is an improvement over the circuit of Figure P7a. The two Zener diodes are identical and have a breakdown voltage of $V_Z = -4$ V and a forward voltage of $V_D = 0.5$ V.
Briefly explain the purpose of the twin Zener diodes and the role of resistor R.

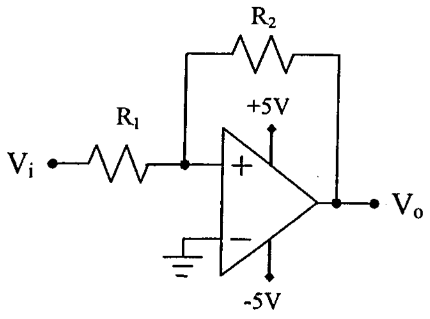

Figure P7a

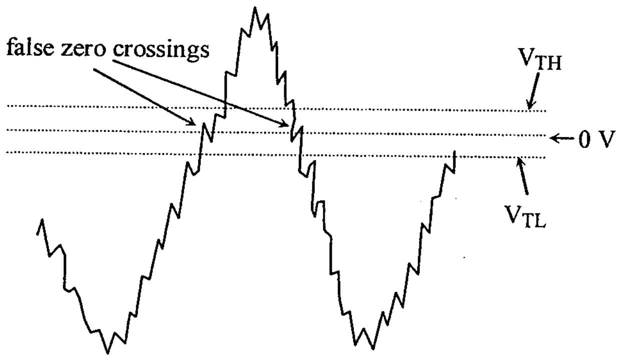

Figure P7b

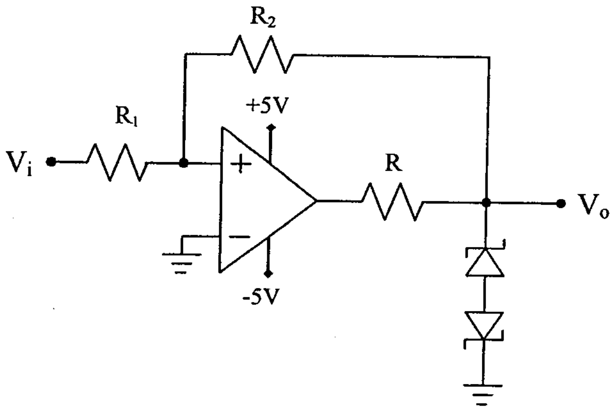

Figure P7c

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ANNEX A: USEFUL CONSTANTS AND EQUATIONS

(1) 1 Å = 10^{-10} m = 10^{-8} cm = 10^{-4} μm
(2) $q = 1.6\text{x}10^{-19}$ C
(3) $k = 1.38 \text{ x } 10^{-23}$ J/°K = $8.62 \text{ x } 10^{-5}$ eV/°K [At T = 300°K, kT = 0.026 eV, $V_T = kT/q \approx 26$ mV]
(4) Avogadro's Number $A_N = 6.02 \text{ x } 10^{23}$ /mole

(5) For silicon (Si) at T = 300 °K: $n_i = 1.5\text{x}10^{10}/\text{cm}^3$
(6) $\varepsilon_{Si} = 1.04\text{x}10^{-12}$ F/cm
(7) $\varepsilon_{SiO2} = 0.345\text{x}10^{-12}$ F/cm [farad: 1 F = 1 C/V] [siemens: 1 mS = 1 mA/V = 1 mmho]

(8) $$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

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

(10) $$n_o p_o = n_i^2$$

(11) $$n_o = N_c e^{(E_F-E_c)/kT} = n_i e^{(E_F-E_i)/kT}$$

(12) $$p_o = N_v e^{(E_v-E_F)/kT} = n_i e^{(E_i-E_F)/kT}$$

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

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

(15) $$W = \sqrt{\frac{2\varepsilon_{Si} V_o}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$$

(16) $$x_{po} = \frac{W N_d}{N_a + N_d} \qquad x_{no} = \frac{W N_a}{N_a + N_d}$$

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

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

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

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

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

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

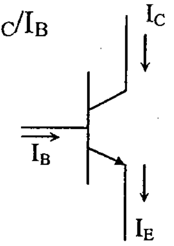
BJT relationships and model

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

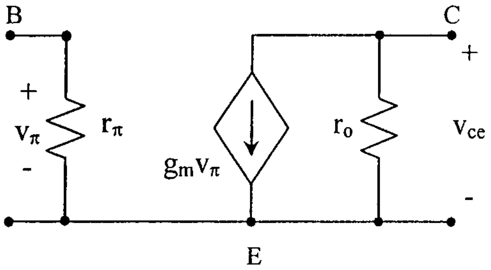
(24) $I_E = I_B + I_C$

(25) $g_m = I_C/V_T$

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



Small signal BJT model



MOS relationships and model

(27) $C_i = \dfrac{\varepsilon_{SiO_2}}{d}$

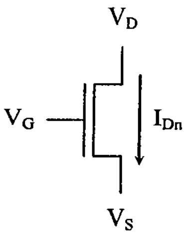
(28) $V_T = \Phi_{ms} + 2\phi_F - \dfrac{1}{C_i}(Q_i + Q_d)$

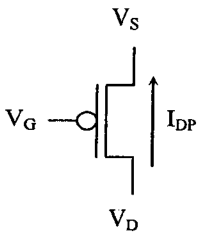
(29) $I_{Dn} = (k_n/2)\,(V_{GSn} - V_{tn})^2$ when $V_{DSn} > V_{GSn} - V_{tn}$

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

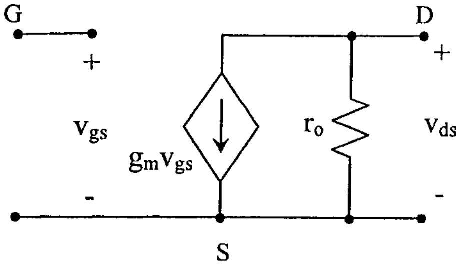
(31) $I_{Dp} = -(k_p/2)\,(V_{GSp} - V_{tp})^2$ when $V_{DSp} < V_{GSp} - V_{tp}$

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





Small signal MOSFET model



(33) For $R = Aj + B$, $|R| = (A^2+B^2)^{1/2}$ and $\phi(R) = tan^{-1}(A/B)$