236

MADE EASY

Leading Institute for ESE, GATE & PSUs

ESE 2025 : Mains Test Series

UPSC ENGINEERING SERVICES EXAMINATION

Electronics & Telecommunication Engineering

Test-1 : Network Theory + Electronic Devices and Circuits [All topics]

Name : ....

Roll No :

Test Centres				Student's Signature
Delhi ☑	Bhopal ☐	Jaipur ☐	Pune ☐	
Kolkata ☐	Hyderabad ☐			

Instructions for Candidates

1. Do furnish the appropriate details in the answer sheet (viz. Name & Roll No).
2. There are Eight questions divided in TWO sections.
3. Candidate has to attempt FIVE questions in all in English only.
4. Question no. 1 and 5 are compulsory and out of the remaining THREE are to be attempted choosing at least ONE question from each section.
5. Use only black/blue pen.
6. The space limit for every part of the question is specified in this Question Cum Answer Booklet. Candidate should write the answer in the space provided.
7. Any page or portion of the page left blank in the Question Cum Answer Booklet must be clearly struck off.
8. There are few rough work sheets at the end of this booklet. Strike off these pages after completion of the examination.

FOR OFFICE USE

Question No.	Marks Obtained
Section-A	
Q.1	30
Q.2	/
Q.3	25
Q.4	/
Section-B	
Q.5	44
Q.6	32
Q.7	24
Q.8	/
Total Marks Obtained	155

Signature of Evaluator — Cross Checked by

Ch.[illegible]

- Avoid Calculation errors.
- Need conceptual clarity.

IMPORTANT INSTRUCTIONS

CANDIDATES SHOULD READ THE UNDERMENTIONED INSTRUCTIONS CAREFULLY. VIOLATION OF ANY OF THE INSTRUCTIONS MAY LEAD TO PENALTY.

DONT'S

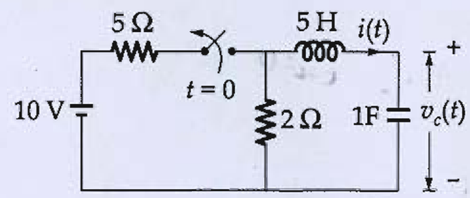
1. Do not write your name or registration number anywhere inside this Question-cum-Answer Booklet (QCAB).
2. Do not write anything other than the actual answers to the questions anywhere inside your QCAB.
3. Do not tear off any leaves from your QCAB, if you find any page missing do not fail to notify the supervisor/invigilator.
4. Do not leave behind your QCAB on your table unattended, it should be handed over to the invigilator after conclusion of the exam.

DO'S

1. Read the Instructions on the cover page and strictly follow them.
2. Write your registration number and other particulars, in the space provided on the cover of QCAB.
3. Write legibly and neatly.
4. For rough notes or calculation, the last two blank pages of this booklet should be used. The rough notes should be crossed through afterwards.
5. If you wish to cancel any work, draw your pen through it or write "Cancelled" across it, otherwise it may be evaluated.
6. Handover your QCAB personally to the invigilator before leaving the examination hall.

Section A : Network Theory + Electronic Devices and Circuits

Q.1 (a) Consider the circuit shown below:



If the equation of current, $i(t) = e^{-\alpha t}[B_1 \cos\omega_d t + B_2 \sin \omega_d t]$ for $t \geq 0$.

Then calculate the value of

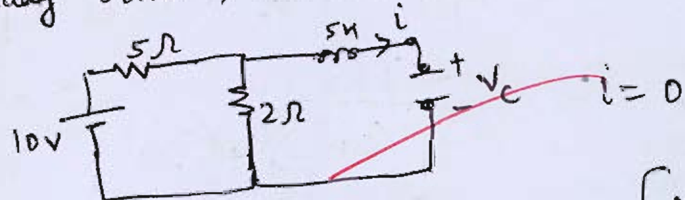
(i) α (ii) B_1

(iii) B_2 (iv) ω_d

[12 Marks]

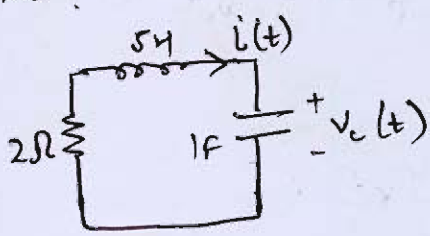
Solⁿ

In steady state, for $t < 0$.



$V_c = 10 \times \frac{2}{5+2} = \frac{20}{7}$ V [voltage division rule]

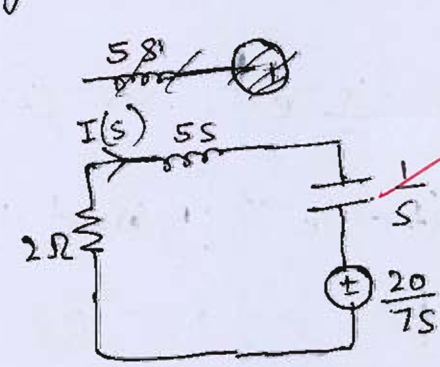
For $t > 0$:



$i(0^+) = 0$

$V_c(0^+) = \frac{20}{7}$ V

Converting the circuit in laplace domain



$$I(s) = \frac{-\frac{20}{7s}}{2 + 5s + \frac{1}{s}}$$

$$I(s) = \frac{-\frac{20}{7S}}{2 + 5S + \frac{1}{S}}$$

$$= \frac{-20}{14S + 35S^2 + 7}$$

$$= \frac{-20}{35\left[S^2 + \frac{2}{5}S + \frac{1}{5}\right]}$$

$$= \frac{-4}{7\left[S^2 + 2\times1\times\frac{1}{5} + \frac{1}{25} - \frac{1}{25} + \frac{1}{5}\right]}$$

$$= \frac{-4}{7\left[\left(S+\frac{1}{5}\right)^2 + \left(\frac{2}{5}\right)^2\right]}$$

$$L^{-1}\left[\frac{\omega_0}{S^2+\omega_0^2}\right] \rightarrow \sin\omega_0 t \; u(t)$$

$$L^{-1}\left[\frac{\omega_0}{(S+a)^2+\omega_0^2}\right] \rightarrow e^{-at}\sin\omega_0 t \; u(t)$$

$$\therefore \quad I(s) = -\frac{4}{7}\times\frac{5}{2}\times\frac{\frac{2}{5}}{\left(S+\frac{1}{5}\right)^2+\left(\frac{2}{5}\right)^2}$$

12

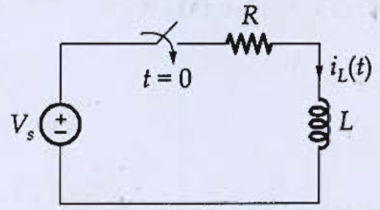
$$i(t) = -\frac{10}{7}e^{-\frac{t}{5}}\sin\frac{2}{5}t \quad u(t)$$

Comparing with $i(t) = e^{-\alpha t}\left[B_1\cos\omega_d t + B_2\sin\omega_d t\right] \; t\geq 0$

(i) $\alpha = \frac{1}{5}$ (ii) $B_1 = 0$

(iii) $B_2 = -\frac{10}{7}$ (iv) $\omega_d = \frac{2}{5}$ rad/sec

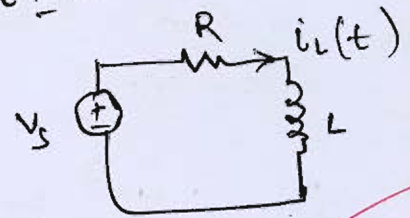
Q.1 (b) Prove that the efficiency of DC excited R-L series circuit is zero.



[12 Marks]

Sol^n

For $t \geq 0$



Applying KVL,

$$V_s - i_L(t) R - L\frac{di_L(t)}{dt} = 0$$

$$L\frac{di_L(t)}{dt} = V_s - i_L(t) R$$

$$\frac{di_L(t)}{\left(\frac{V_s}{R} - i_L(t)\right)} = \frac{R}{L} dt$$

$$\Rightarrow \quad i_L(t) = \frac{V_s}{R}\left[1 - e^{-Rt/L}\right]$$

$$\text{Average output Power} = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} i_L^2 R \, dt$$

$$= \frac{1}{T}\int_{-T/2}^{T/2} \frac{V_s^2}{R^2}\left[1 + e^{-\frac{2Rt}{L}} - 2e^{-Rt/L}\right] R$$

$$= \lim_{T\to\infty} \frac{V_s^2}{RT}\left[t - e^{-\frac{2Rt}{L}} \cdot \left(\frac{2R}{L}\right) + \frac{2R}{L} e^{-\frac{Rt}{L}}\right]$$

$$= \lim_{T\to\infty} \frac{V_s^2}{RT}\left[T - \frac{2R}{L} e^{-\frac{2R}{L}(T/2)} + \frac{2R}{L} e^{\frac{2RT}{L2}} + \frac{2R}{L}\left(e^{-\frac{RT}{2L}} - e^{+\frac{RT}{2L}}\right)\right]$$

$\therefore$ Average output power (DC) $= \frac{V_s^2}{R}$

AC output power = Total Power − DC power

$= \frac{V_s^2}{R} - \frac{V_s^2}{R}$

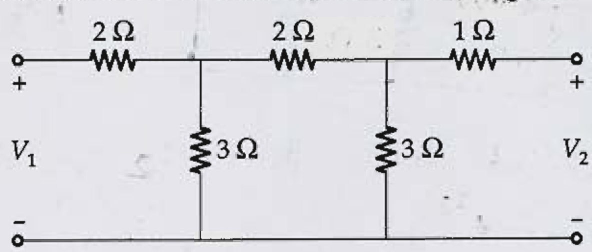
$= 0$

8

$\therefore \eta = \frac{0}{\left(\frac{V_s^2}{R}\right)} \times 100 = 0.$

Do not write in this margin

Q.1 (c) Obtain *ABCD* parameters for the network shown in figure.



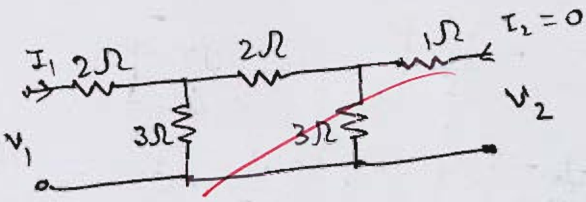
[12 marks]

Sol^n

$$V_1 = AV_2 - BI_2$$

$$I_1 = CV_2 - DI_2$$

$I_2 = 0$:



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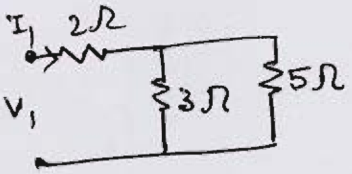

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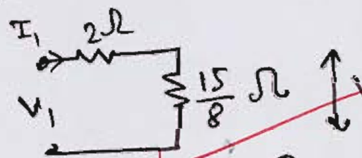


— (A)

$$V = \frac{\frac{15}{8} V_1}{2 + \frac{15}{8}}$$

$$\boxed{V = \frac{15 V_1}{31}}$$

From voltage division rule,

$$V_2 = \frac{3}{5} V = \frac{3}{5} \times \frac{15}{31} V_1$$

$$\boxed{V_2 = \frac{9}{31} V_1} \Rightarrow \boxed{A = \left.\frac{V_1}{V_2}\right|_{I_2=0} = \frac{31}{9}}$$

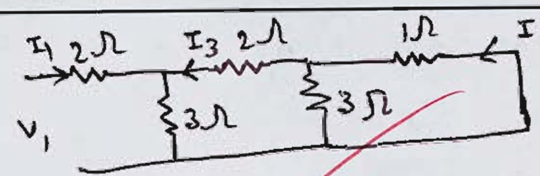
From circuit (A)

$$\frac{V_1}{I_1} = 2 + \frac{15}{8} = \frac{31}{8} \Omega$$

$$\therefore \frac{I_1}{V_2} = \frac{I_1}{V_1} \times \frac{V_1}{V_2} = \frac{8}{31} \times \frac{31}{9} = 8/9$$

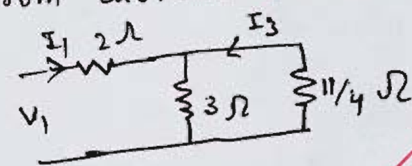
$$\therefore \boxed{C = \left.\frac{I_1}{V_2}\right|_{I_2=0} = \frac{8}{9}}$$

$V_2 = 0$:



$B = -\frac{V_1}{I_2}\Big|_{V_2=0}$

From current division rule, $I_2 = \frac{3}{4} I_3$



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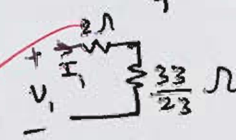


$\frac{V_1}{I_1} = \frac{79}{23}$

$$I_3 = -I_1 \times \frac{3}{3+\frac{11}{4}} = \frac{-3 I_1 \times 4}{23}$$

$$\therefore\ I_2 = \frac{-12}{23} \times \frac{3}{4} I_1 = \frac{-9}{92} I_1$$

$$\left[D = -\frac{I_1}{I_2}\Big|_{V_2=0} = \frac{92}{9} \right]$$

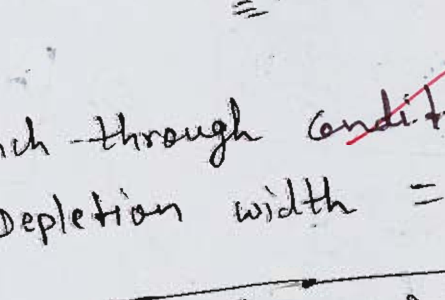
$$\left[B = -\frac{V_1}{I_2}\Big|_{V_2=0} = \frac{-V_1}{I_1} \cdot \frac{I_1}{I_2} = \frac{79}{23} \times \frac{92}{9} = \frac{316}{9} \right]$$

Q.1 (d) Consider an n-channel MOSFET with source and drain doping concentrations of $N_d = 10^{19}$ cm^{-3} and a channel region doping of $N_a = 10^{16}$ cm^{-3}. Assume a channel length of $L = 1.2$ μm, and assume the source and body are at ground potential (i.e, $|V_{SB}| = 0$). Calculate the theoretical punch-through voltage assuming the abrupt junction approximation.

(Assume, $V_T = 0.0259\ V$; $\epsilon_S = 11.7\epsilon_0$; $n_i = 1.5 \times 10^{10}$ cm^{-3} for Si)

[12 Marks]

Sol^n:



For Punch-through condition:
Depletion width = channel length

$$W = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_p + V_0)}$$

4

$$V_0 = V_T \ln \frac{N_a N_d}{n_i^2}$$

$$= 0.0259 \ln\left(\frac{10^{19} \times 10^{16}}{2.25 \times 10^{20}}\right)$$

$$= 0.0259 \ln\left(\frac{10^{15}}{2.25}\right)$$

$$= 0.0259 \left[15 \ln 10 - \ln(2.25)\right]$$

$$\boxed{V_0 = 0.873\,V}$$

$$\therefore\ 1.2 \times 10^{-4} = \sqrt{\frac{2 \times 11.7 \times 8.854 \times 10^{-14}}{1.6 \times 10^{-19}}\left(\frac{1}{10^{19}} + \frac{1}{10^{16}}\right)(V_p + V_0)}$$

$$\approx \sqrt{129.489 \times 10^{5} \times 10^{-16}(V_p + V_0)}$$

$$1.44 \times 10^{-8} \approx 129.489 \times 10^{-11}(V_p + V_0)$$

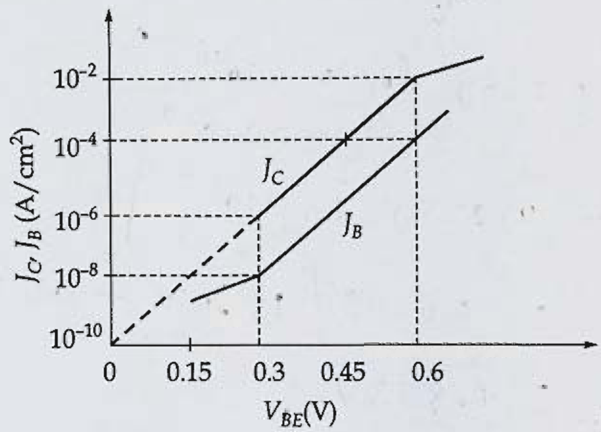
$$11.12 = V_p + V_0$$

$$\therefore\ V_p = 11.2 - 0.873 = 10.247\,V$$

~~$V_p = 10.25\,V$~~

$$\boxed{V_p \approx 10.25\,V}$$

Q.1 (e) Consider an NPN transistor with Emitter, Base and Collector region width as $W_E = 0.5\ \mu m$, $W_B = 0.2\ \mu m$ and $W_C = 2\ \mu m$ respectively. Diffusion coefficient of carriers in base region, $D_B = 10\ cm^2/s$.



Calculate:

(i) Common Emitter Current gain, β.

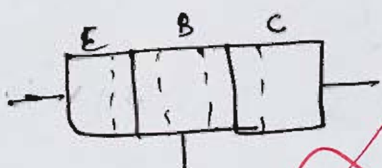
(ii) Base doping concentration, N_B.

(iii) Base transit time, τ_B.

(Assume, $W_B << L_B$, $n_i = 10^{10}\ cm^{-3}$; $\frac{kT}{q} = 0.026\ V$)

[12 Marks]

Sol^n



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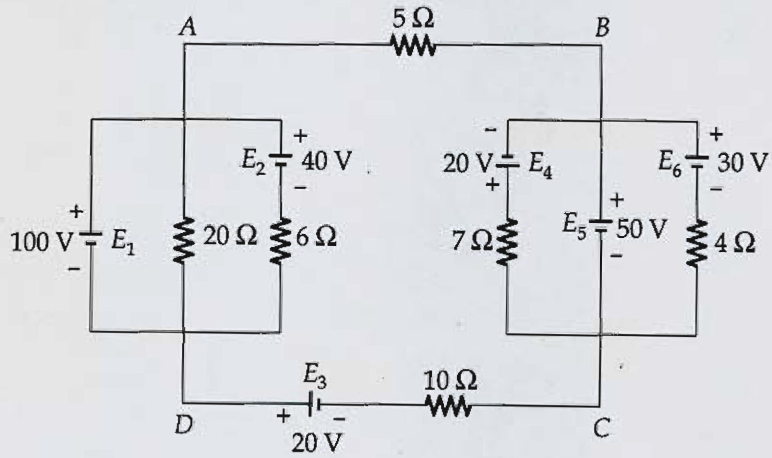
Q.2 (a) For the circuit shown in figure, find the current through 5 Ω resistor by using Thevenin's theorem and verify the same by using superposition theorem.



[20 marks]

Q.2 (b) Consider an n-channel MOSFET with a doping of $N_a = 10^{15}$ cm^{-3}, an oxide thickness of $t_{ox} = 750$Å and an initial flat-band voltage of $V_{FB} = -1.5$ V.

Calculate:

(i) Threshold voltage, V_T.

(ii) The ion implant density 'D_I' required to achieve a threshold voltage of $V_T = +0.9\ V$ with $V_{SB} = 0$.

(iii) Using the result obtained in part (ii), determine the threshold voltage if source to body voltage, $V_{SB} = 2$ V is applied.

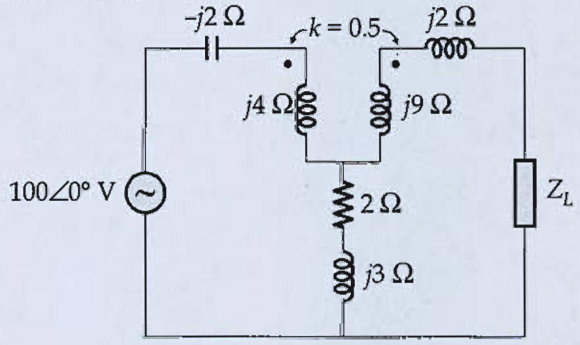
(Assume, $V_t = 0.026$ V, $\epsilon_s = 11.7\,\varepsilon_0$, $\epsilon_{0x} = 3.9\epsilon_0$, $n_i = 1.5 \times 10^{10}$ cm^{-3})

[8 + 4 + 8 marks]

Do not write in this margin

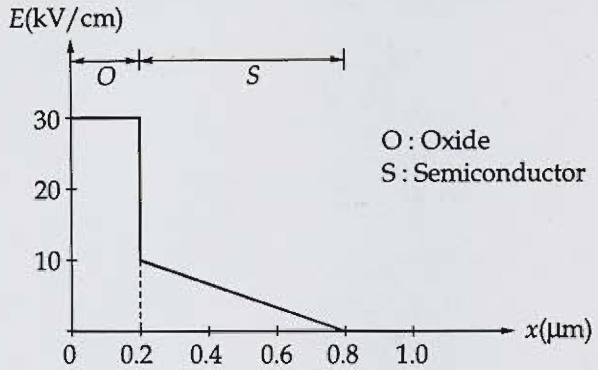
Q.2 (c) **(i)** Find the Thevenin's equivalent of the circuit shown in figure below as seen from the load impedance Z_L.

(ii) Find the value of Z_L for maximum power transfer and also the maximum power transfer to the load Z_L.



[12 + 8 marks]

Q.3 (a) The figure shows the electric field distribution within a MOS structure (P-substrate) for a given potential V_G applied to the gate. Assume the flat band potential $V_{FB} = 0$.



Find:

(i) The potential in the bulk of the semiconductor ψ_B.

(ii) The potential at the surface of semi conductor, ψ_s.

(iii) The threshold voltage, V_T.

(iv) The value of the applied potential at Gate, V_G.

(Assume, $\epsilon_{si} = 10^{-12}$ F/cm; $\epsilon_{ox} = 3 \times 10^{-13}$ F/cm, $n_i = 1.5 \times 10^{10}$ cm^{-3}, $C_{ox} = 15$ nF/cm^2, $V_T = 26$ mV)

[20 marks]

Sol^n

(i) $E = 0$ for $x > 0.8\ \mu m$

As flat band ~~volt~~ potential $= 0$

1

$\therefore$ Potential in the bulk $= 0$

$$\boxed{\psi_B = 0}$$

(ii) Potential at the surface

2

$$\psi_s = \frac{1}{2} \times (0.8 - 0.2) \times 10^{-6} \times \frac{10 \times 10^3}{10^{-2}}\ V$$

$$= \frac{1}{2} \times 0.6\ V$$

$$\boxed{\psi_s = -0.3\ V}$$

$\psi_s = -0.3$

Do not write in this margin

~~iii) Q_d =~~

(iv) $V_G = \frac{30\times10^3}{10^{-2}} \times 0.2\times10^{-6} + \psi_s$

$= 6\times10^{-1} + \psi_s$

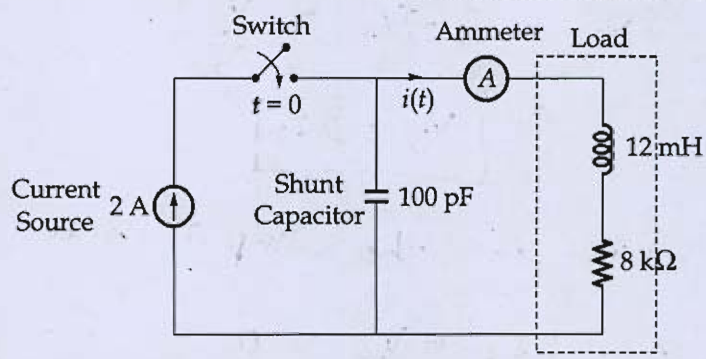
$= 0.6 + 0.3$

3

$$\boxed{V_G = 0.9\,V}$$

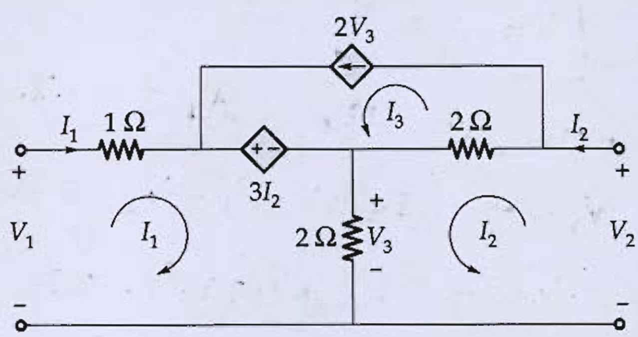
Do not write in this margin

Q.3 (b) (i) The circuit in the figure contains a current source driving a load having an inductor and a resistor in series, with a shunt capacitor across the load. The ammeter is assumed to have zero resistance. The switch is closed at time $t = 0$.



Initially, when the switch is open, the capacitor is discharged and the ammeter reads zero ampere. After the switch is closed, the ammeter reading keep fluctuating for some time till it settle to a final steady value. Calculate the maximum ammeter reading that one will observe after the switch is closed.

(ii) Determine Z and Y-parameters of the network shown in figure.



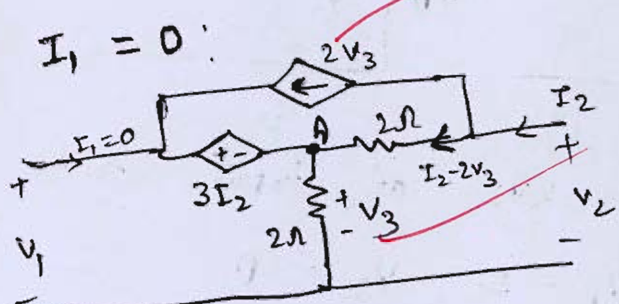
[10 + 10 marks]

Sol^n

(i) ~~In steady~~

ii)
$$V_1 = Z_{11} I_1 + Z_{12} I_2$$
$$V_2 = Z_{21} I_1 + Z_{22} I_2$$

Taking $I_1 = 0$:



Applying KCL at node A.

$$2V_3 + I_2 - 2V_3 = \frac{V_3}{2}$$

$$\Rightarrow \boxed{V_3 = 2I_2}$$

Applying KVL in the input side

$$V_1 - 3I_2 - V_3 = 0$$

$$V_1 - 3I_2 - 2I_2 = 0$$

$$V_1 = 5I_2 \Rightarrow \boxed{\frac{V_1}{I_2} = 5}$$

$$\therefore \boxed{Z_{12} = 5\,\Omega}$$

5

Applying KVL at the output side

$$V_2 - 2(I_2 - 2V_3) - V_3 = 0$$

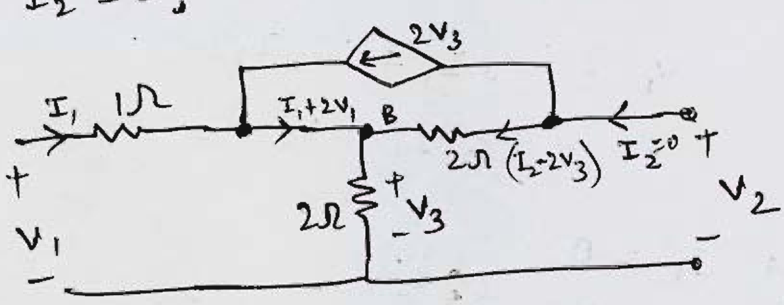
$$V_2 - 2I_2 + 4(2I_2) - 2I_2 = 0$$

$$V_2 = 4I_2 \Rightarrow \frac{V_2}{I_2} = 4$$

$$\therefore \boxed{Z_{22} = 4\,\Omega}$$

$-4\,\Omega$

Taking $I_2 = 0$:



Applying KVL at input side

$$V_1 - I_1 - V_3 = 0 \quad \text{—(i)}$$

Applying KCL at node B.

$$I_1 + 2V_1 + I_2 - 2V_3 = \frac{V_3}{2}$$

$\because I_2 = 0$

$$\Rightarrow \quad I_1 + 2V_1 = \frac{5V_3}{2}$$

$$\Rightarrow V_3 = \frac{2}{5}(I_1 + 2V_1)$$

$\therefore$ from equation (i)

$$V_1 - I_1 = \frac{2}{5}I_1 + \frac{4V_1}{5}$$

$$\frac{V_1}{5} = \frac{7}{5}I_1$$

$$\Rightarrow \boxed{\frac{V_1}{I_1} = 7}$$

$$\therefore \boxed{Z_{11} = 7}$$

Applying KVL at output side

$$V_2 - 2(-2V_3) - V_3 = 0$$

$$V_2 = -3V_3$$

$$\Rightarrow V_2 = -3 \times \frac{2}{5}(I_1 + 2V_1)$$

$$= -\frac{6}{5}I_1 - \frac{12}{5}V_1$$

$$\frac{V_2}{I_1} = -\frac{6}{5} - \frac{12}{5}\left(\frac{V_1}{I_1}\right)$$

$$= -\frac{6}{5} - \frac{12}{5} \times 7$$

$$= -\frac{90}{5} = -18$$

$$\therefore \boxed{Z_{21} = -18\,\Omega}$$

$$\therefore \; Z = \begin{bmatrix} 7 & 5 \\ -18 & 4 \end{bmatrix}$$

We know, $[Y] = [Z]^{-1}$

$$\text{Cofactor matrix of } Z = \begin{bmatrix} 4 & 18 \\ -5 & 7 \end{bmatrix}$$

$$\text{Adj}(Z) = \begin{bmatrix} 4 & -5 \\ 18 & 7 \end{bmatrix}$$

So $|Z| = 28 + 90 = 118$

$$\therefore \; Z^{-1} = \frac{1}{118} \begin{bmatrix} 4 & -5 \\ 18 & 7 \end{bmatrix}$$

$$\therefore \; Y = \begin{bmatrix} 4/118 & -5/118 \\ 18/118 & 7/118 \end{bmatrix}$$

Do not write in this margin

Q.3 (c) (i) Explain the working principle of a *pn*-junction solar cell.

(ii) Consider an ideal silicon *pn*-junction diode with the following parameters:

$\tau_{n_0} = \tau_{p_0} = 0.1 \times 10^{-6}\, s$

$D_n = 25\ cm^2/s$

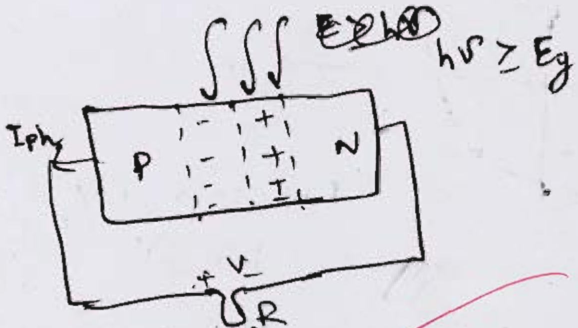
$D_p = 10\ cm^2/s$

If N_d represents donor concentration and N_a represents acceptor concentration, what must be the ratio of $\frac{N_a}{N_d}$ so that 95 percent of the current in the depletion region is carried by electrons?

[10 + 10 marks]

Sol^n

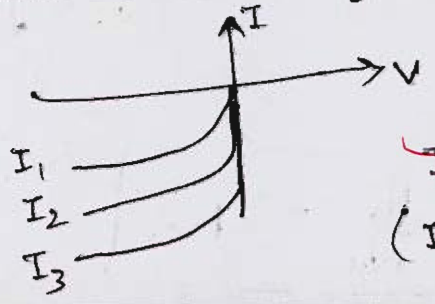
(i)



When light falls on the depletion region of the p-n junction, then large amount of carriers (electron hole pairs) are generated (Energy of incident photon should be greater than bandgap (E_g) of the semiconductor.

These generated charge carrier will be drifted in the presence of built-in electric field and produce electric current.

The generated photocurrent will be proportional to intensity of light.



$I_3 > I_2 > I_1$ (Intensity of light)

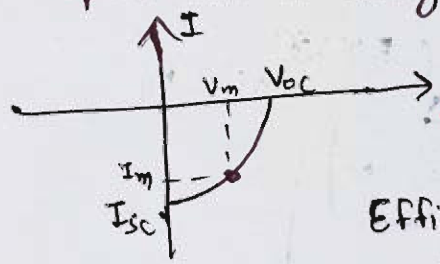
Total current $(I) = I_0(e^{V/V_T} - 1) - I_{ph}$

$I_0(e^{V/V_T} - 1)$ → Due to forward biasing

I_{ph} → Due to optical generation

Short circuit current $(I_{sc}) = -I_{ph}$

open-circuit voltag $(V_{oc}) = V_T \ln\left(1 + \frac{I_{ph}}{I_0}\right)$



Efficiency of Solar cell $(\eta) = \frac{V_m I_m}{P_{in}}$

Fill factor $= \frac{V_m I_m}{V_{oc} I_{oc}}$

ii) $I_{pn} = qA\left[\sqrt{\frac{D_p}{\tau_p}} \frac{n_i^2}{N_D}\right]$ → Due to holes

$I_{np} = qA\left[\sqrt{\frac{D_n}{\tau_n}} \frac{n_i^2}{N_A}\right]$ → Due to electrons.

$\frac{I_{np}}{I_{pn}} = 0.95$

$\Rightarrow \sqrt{\frac{D_n}{\tau_n}} \times \frac{1}{N_a} \times \sqrt{\frac{\tau_p}{D_p}} N_d = 0.95$

$\frac{N_a}{N_d} = \frac{1}{0.95}\sqrt{\frac{D_n}{D_p}}\sqrt{\frac{\tau_p}{\tau_n}}$

$= \frac{1}{0.95}\sqrt{\frac{25}{10}}\sqrt{\frac{10^{-7}}{10^{-7}}}$

$= \frac{5}{0.95\sqrt{10}}$

$\Rightarrow \boxed{\frac{N_a}{N_d} = 1.66}$

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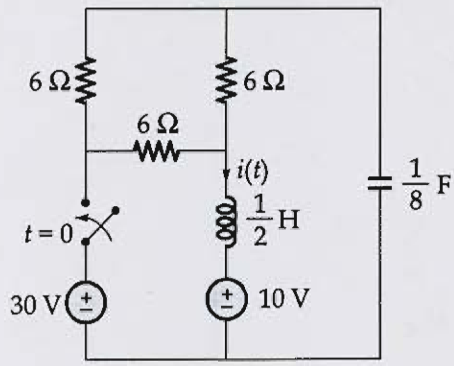
Q.4 (a) For the network shown in figure, solve for $i(t)$ for $t > 0$.



[20 marks]

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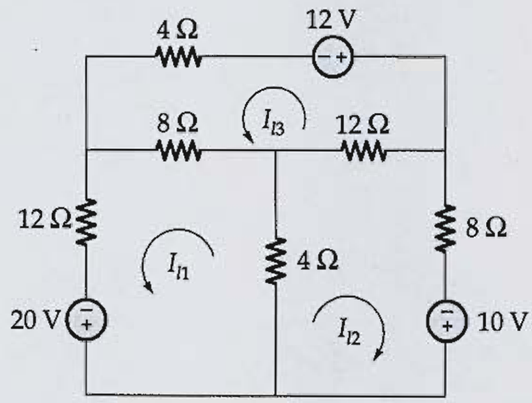
Q.4 (b) For the network shown in figure, write down the tie set matrix, obtain the network equilibrium equations in matrix form using the tie-set matrix and calculate loop currents.



[20 marks]

Q.4 (c) **(i)** Consider a semiconductor in thermal equilibrium (no current). Assume that the donor concentration varies exponentially as,

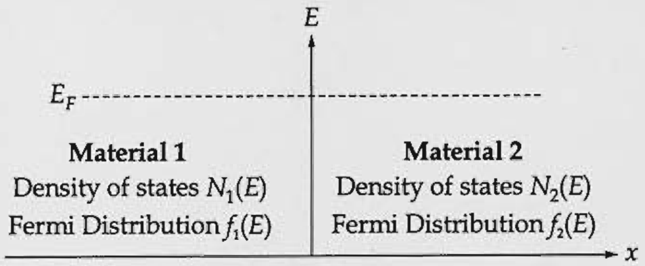
$N_d(x) = N_{d_0} e^{-\alpha x}$

over the range $0 \le x \le \frac{1}{\alpha}$ where N_{d_0} is a constant.

1. Calculate the electric field as a function of 'x' for $0 \le x \le \frac{1}{\alpha}$.

2. Calculate the potential difference between $x = 0$ and $x = \frac{1}{\alpha}$.

(ii) Consider two materials in intimate contact at equilibrium as shown below.



Assume the net motion of electrons is zero, show that the equilibrium Fermi level must be constant throughout, that is, $E_{F_1} = E_{F_2}$ (or) show that no gradient exists in the Fermi level at equilibrium, $\frac{dE_F}{dx} = 0$

[10 + 10 marks]

Section B : Network Theory + Electronic Devices and Circuits

Q.5 (a) Consider a sample of silicon at T = 300 K. A hall effect device is fabricated with the following geometry:

$d = 5 \times 10^{-3}$ cm
$W = 5 \times 10^{-2}$ cm
$L = 0.50$ cm

The electrical parameters measured are:

$I_x = 0.50$ mA
$V_x = 1.25$ V
$B_z = 650$ gauss $= 6.5 \times 10^{-2}$ tesla

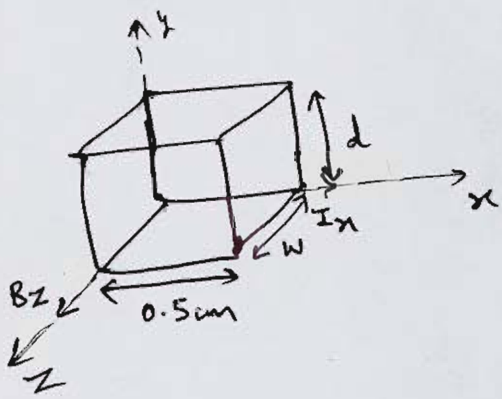
The Hall field is $E_H = -16.5$ mV/cm

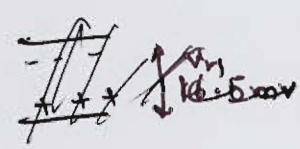
Determine:

(i) the Hall voltage,
(ii) the conductivity type,
(iii) the majority carrier concentration,
(iv) the majority carrier mobility.

[12 marks]

Sol^n





(i) Hall voltage $(V_H) = \frac{BI}{\rho W}$

or $V_H = -E_H \times d$

$= +16.5 \times 10^{-3} \times 5 \times 10^{-3}$

$V_H = 82.5 \times 10^{-6}$ V

(ii) Hall field is in $-y$ direction.

Assuming P-type semiconductor,

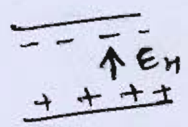
Force on holes $= q(V_x \hat{i} \times B_z \hat{k})$

$= qV_x B_z(-\hat{j})$

which is in $-y$ direction

$\Rightarrow$ Holes depositing in $-\hat{y}$

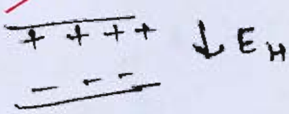
$\Rightarrow$ Hall field in $+y$ direction



So, our assumption is wrong.

$\therefore$ electrons are the majority carrier

$\Rightarrow$ [n-type conductivity]



(iii) $V_H = \frac{BI}{\rho W}$

$\Rightarrow \rho = \frac{BI}{V_H W} = \frac{6.5\times10^{-2}\times0.5\times10^{-3}}{82.5\times10^{-6}\times5\times10^{-2}}$

$= 7.88\ C/cm^3$

Majority carrier Concentration $= \frac{7.88}{1.6\times10^{-19}}$

$= 4.92\times10^{19}/cm^3$

10

Q.5 (b) Consider a long silicon *pn*-junction photodiode at T = 300 K with the following parameters:

$N_a = 2 \times 10^{16}\ cm^{-3}$ $N_d = 10^{18}\ cm^{-3}$

$D_n = 25\ cm^2/s$ $D_p = 10\ cm^2/s$

$\tau_{n_0} = 2 \times 10^{-7}\ s$ $\tau_{p_0} = 10^{-7}\ s$

Assume a reverse-bias voltage of V_R = 5 volts is applied and assume a uniform generation rate of $G_L = 10^{21}\ cm^{-3}\ s^{-1}$ exists throughout the entire photodiode.

Calculate:

(i) The prompt photocurrent density and

(ii) The total steady-state photocurrent density.

Given: n_i for $Si = 1.5 \times 10^{10}\ cm^{-3}$

$\varepsilon_{r_{si}} = 11.7$

[12 marks]

Sol^n

$$L_p = \sqrt{D_p \tau_p} = \sqrt{10^{-6}} = 10^{-3}\ cm$$

$$L_n = \sqrt{D_n \tau_n} = \sqrt{5 \times 10^{-6}} = 2.34 \times 10^{-3}\ cm$$

$$V_0 = V_T \ln \frac{N_a N_D}{n_i^2}$$

$$= 0.0259 \ln\left(\frac{2 \times 10^{16} \times 10^{18}}{2.25 \times 10^{20}}\right)$$

$$= 0.0259 \ln\left(\frac{2 \times 10^{14}}{2.25}\right)$$

$$\boxed{V_0 = 0.83\ V}$$

Width of depletion region

$$W = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + V_R)}$$

$$= \sqrt{\frac{2 \times 11.7 \times 8.854 \times 10^{-14}}{1.6 \times 10^{-19}}\left(\frac{10^{-16}}{2} + \frac{10^{-18}}{1}\right)(5.83)}$$

$$= \sqrt{754.92 \times 10^{5} \times 51 \times 10^{-18}}\ cm$$

$[W = 62.05 \times 10^{-6}\ cm]$

(i) Prompt photocurrent density

$= q\, G_{op} [W]\ A/cm^2$

$= 1.6\times10^{-19} \times 10^{21} \times 62.05\times10^{-6}$

$= 99.28 \times 10^{-4}\ A/cm^2$

$[J \simeq 9.93\ mA/cm^2]$

(ii) Total ~~photocu~~ steady-state photocurrent density

$= q\, G_{op} [L_n + W + L_p]$

$\approx 1.6\times10^{-19}\times10^{21}\times 3.34\times10^{-3}\ A/cm^2$

$\simeq 0.534\ A/cm^2$

$[J_{Total} = 534\ mA/cm^2]$

12

Q.5 (c) (i) Calculate the temperature at which there is a 10^{-6} probability that an energy state 0.55 eV above the Fermi energy level is occupied by an electron.

(ii) A silicon n^+p junction is biased at $V_R = 10$ V.
Determine the ΔV_{bi} (Change in built-in potential), if the doping in the p-region increases by a factor of 2.

[6 + 6 marks]

Soln

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

(i) $E - E_F = 0.55eV$

$\Rightarrow 10^{-6} = \frac{1}{1+e^{\Delta E/KT}}$

$1 + e^{\Delta E/KT} = 10^6$

$\Rightarrow e^{\Delta E/KT} \approx 10^6$

$\frac{\Delta E}{KT} \simeq 6 \ln 10$

$T = \frac{\Delta E}{K \times 6\ln 10} = \frac{0.55\times1.6\times10^{-19}}{1.38\times10^{-23}\times13.81}$

$T \simeq 0.04617\times10^4\ K$

6

Do not write in this margin

$$T = 461.73\ K$$

ii)

$$V_0 = V_T \ln\left(\frac{N_a N_D}{n_i^2}\right)$$

$$= V_T \ln\left(\frac{N_a}{\;}\right) + V_T \ln\left(\frac{N_D}{n_i^2}\right)$$

$$V_{01} = V_T \ln N_{a_1} + V_T \ln \frac{N_D}{n_i^2}$$

$$V_{02} = V_T \ln N_{a_2} + V_T \ln \frac{N_D}{n_i^2}$$

$$\therefore \quad \Delta V_{bi} = V_{02} - V_{01} = V_T \ln N_{a_2} - V_T \ln N_{a_1}$$

$$= V_T \ln\left(\frac{N_{a_2}}{N_{a_1}}\right) = V_T \ln 2$$

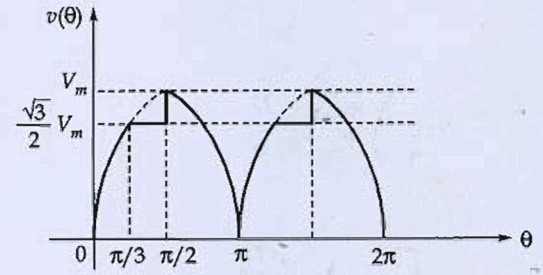
$$\Delta V_{bi} = V_T \ln 2$$

Assuming $V_T = 0.0259\ V$ at $T = 300\ K$

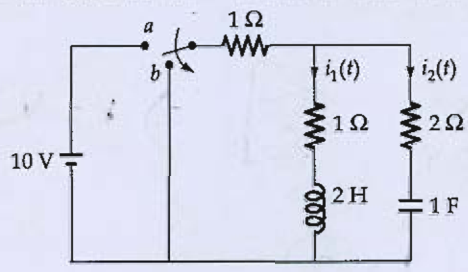
$$\Delta V_{bi} = 17.95\ mV$$

6

Q.5 (d) **(i)** The periodic function $v(\theta)$ given below is applied to a resistor of 1 Ω. Calculate the power dissipated in the resistor.
[Given, $V_m = 1$ V]



(ii) In the circuit shown below, at $t = 0$, the switch is moved from position 'a' to 'b'.



Determine the value of $\frac{di_1(0^+)}{dt}$.

[6 + 6 Marks]

Sol^n

(i) Power dissipated $= \frac{1}{\pi} \int_0^{\pi} \frac{v^2(\theta)}{1} d\theta$

$$= \frac{1}{\pi} \left[\int_0^{\pi/3} V_m^2 \sin^2\theta \, d\theta + \int_{\pi/3}^{\pi/2} \left(\frac{\sqrt{3}}{2} V_m\right)^2 d\theta + \int_{\pi/2}^{\pi} V_m^2 \sin^2\theta \, d\theta \right]$$

$$= \frac{1}{\pi} \left\{ \frac{V_m^2}{2} \left[\int_0^{\pi/3} (1 - \cos 2\theta) d\theta \right] + \frac{3}{4} V_m^2 \times \frac{\pi}{6} + \frac{V_m^2}{2} \left[\int_{\pi/2}^{\pi} (1 - \cos 2\theta) d\theta \right] \right.$$

using: $2\sin^2\theta = 1 - \cos 2\theta$

$$P = \frac{1}{\pi} \left[\frac{V_m^2}{2} \left[\theta - \frac{\sin 2\theta}{2} \right]_0^{\pi/3} + \frac{\pi}{8} V_m^2 + \frac{V_m^2}{2} \left[\theta - \frac{\sin 2\theta}{2} \right]_{\pi/2}^{\pi} \right]$$

$$P = \frac{1}{\pi}\left[\frac{V_m^2}{2}\left(\frac{\pi}{3} - \frac{\sqrt{3}}{4}\right) + \frac{\pi V_m^2}{8} + \frac{V_m^2}{2}\left(\frac{\pi}{2}\right)\right]$$

$$P = \frac{V_m^2}{\pi}\left[\frac{1}{2}\left(\frac{\pi}{3} - \frac{\sqrt{3}}{4}\right) + \frac{\pi}{8} + \frac{\pi}{4}\right]$$

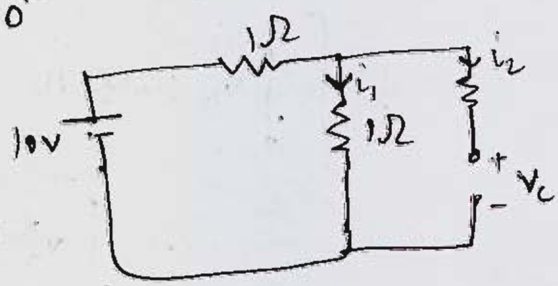
$$= \frac{V_m^2}{\pi}\left[\frac{\pi}{6} - \frac{\sqrt{3}}{8} + \frac{3\pi}{8}\right]$$

$$P = \frac{V_m^2}{\pi}\left[\frac{13\pi}{24} - \frac{\sqrt{3}}{8}\right] \Rightarrow P = V_m^2\left[\frac{13}{24} - \frac{\sqrt{3}}{8\pi}\right]$$

$V_m = 1$ (given)

$$\boxed{P = 0.473\ W}$$

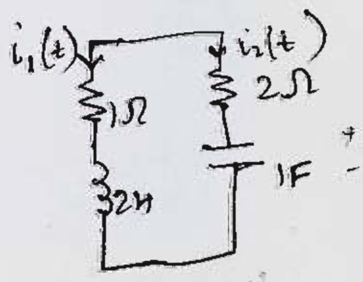
ii) At $t = 0^-$



$$i_1(0^-) = \frac{10}{2} = 5A$$

$$V_c(0^-) = 5V$$

At $t = 0^+$



$i_1'(0^+) = 5A$, $V_c(0^+) = 5V$

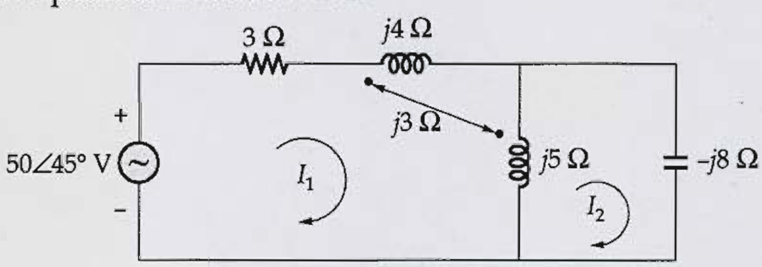
Applying KVL in the circuit,

$$-1 \times i_1'(0^+) - 2\frac{di_1(0^+)}{dt} + V_c(0^+) - 2i_1'(0^+) = 0$$

$$-5 - 2\frac{di_1'(0^+)}{dt} + 5 - 10 = 0$$

$$\Rightarrow \frac{di_1'(0^+)}{dt} = -5 \text{ A/s}$$

Q.5 (e) For the network shown in figure, write down the tie set matrix and obtain network equilibrium equations in matrix from.



[12 marks]

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Q.6 (a) **(i)** A series resonant circuit has its impedance,

$$Z(s) = \frac{20(s+1+j10)(s+1-j10)}{s}$$

Find:

- Resonant frequency
- Q-factor
- Bandwidth
- Impedance of the circuit under resonance condition

(ii) Draw a parallel RLC circuit using the elements of $Z(s)$. And also calculate the extra capacitance (C_{ext}) that must be added in series with capacitor C so that the resonant frequency of parallel RLC circuit is increased by factor of 5.

[10 + 10 marks]

Sol^n

(i)

$$Z(s) = \frac{20\left[(s+1)^2 - (j10)^2\right]}{s}$$

$= 20[$ ~~s~~

$s = j\omega$

$$Z(j\omega) = \frac{20\left[(1+j\omega)^2 + 100\right]}{j\omega}$$

$$= 20\left[\frac{1-\omega^2+j2\omega+100}{j\omega}\right]$$

$$Z(j\omega) = 20\left[2 - j\left(\frac{101-\omega^2}{\omega}\right)\right]$$

At resonance, $Im(Z(j\omega)) = 0$

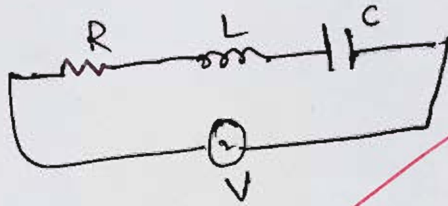
$\Rightarrow \omega = \sqrt{101}$ rad/s

$$f = \frac{\sqrt{101}}{2\pi}$$

$$\boxed{f = 1.6\ Hz}$$

Impedance at resonance $= 40\,\Omega$

Series R-L-C



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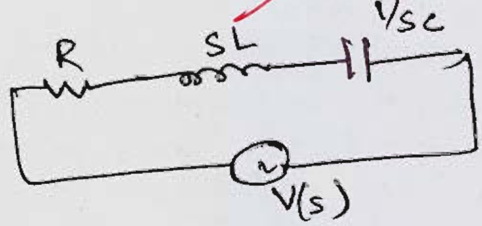


$$Z(s) = R + SL + \frac{1}{SC}$$

$$= \frac{RCS + S^2LC + 1}{SC}$$

$$= \frac{S^2LC + RCS + 1}{SC} = \frac{L\left[S^2 + \frac{R}{L}S + \frac{1}{LC}\right]}{S}$$

Given, $Z(s) = \frac{20(s+1+j10)(s+1-j10)}{s}$

$$= \frac{20\left[(s+1)^2 + 100\right]}{s}$$

$$= \frac{20\left[s^2 + 2s + 101\right]}{s}$$

On comparison,

$L = 20$, $\frac{R}{L} = 2 \Rightarrow R = 40$, $C = 1$

10

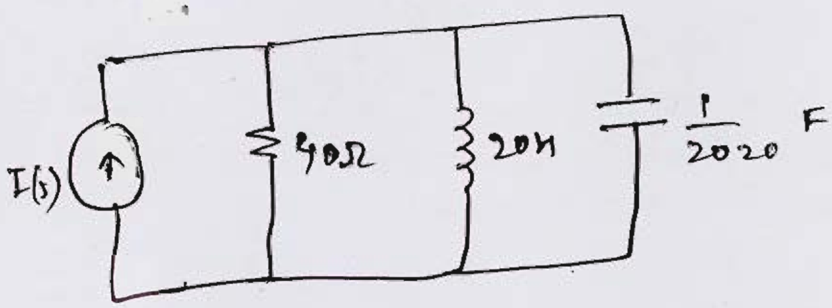
$$\text{Bandwidth} = \frac{R}{2\pi L} = \frac{1}{\pi} = 0.318 \text{ Hz}$$

$$\text{Quality factor} = \frac{\omega L}{R} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

$$= \frac{\sqrt{101}}{2} = 5.02$$

$$\frac{1}{LC} = 101 \Rightarrow C = \frac{1}{101 \times 20} = \frac{1}{2020} F$$

(ii)



$$\frac{1}{\sqrt{LC_2}} = 5 \times \frac{1}{\sqrt{LC_1}}$$

$$C_2 = \frac{C_1}{25} = \frac{1}{2020 \times 25}$$

$$\frac{1}{C_{ex}} + \frac{1}{C_1} = \frac{1}{C_2}$$

$$\frac{1}{C_{ex}} + 2020 = 2020 \times 25$$

$$\frac{1}{C_{ex}} = 24 \times 2020$$

$$\Rightarrow C_{ex} = \frac{1}{24 \times 2020} = 2.06 \times 10^{-5} F$$

∴ 2.06×10^{-5} F extra capacitance must be added in series with capacitance C.

10

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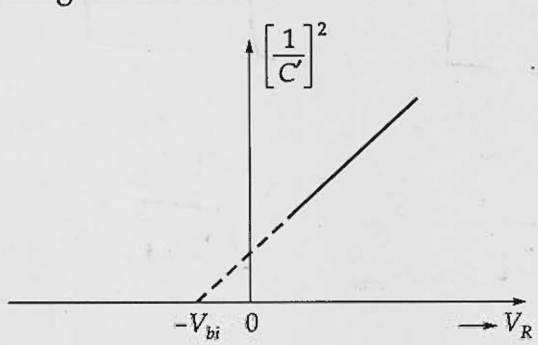
Q.6 (b) (i) A silicon device with n-type material is to be operated at $T = 550$ K. At this temperature, the intrinsic carrier concentration must contribute no more than 5 percent of the total electron concentration. Determine the minimum donor concentration to meet this specification.

(Given : $n_i = 3.20 \times 10^{14}$ cm^{-3} at $T = 550$ K) [3.84 × 10^15]

(ii) Assume a silicon p^+n junction at $T = 300$ K with $n_i = 1.5 \times 10^{10}$ cm^{-3}. The inverse depletion layer capacitance per unit area squared is a linear function of applied reverse-bias voltage as shown below.



Assume that the intercept of the curve on the voltage axis in above figure gives −0.855 V and that the slope is 1.32×10^{15} (F/cm^2)$^{-2}$V^{-1}.

Determine the impurity doping concentrations 'N_d' and 'N_a'.

[Given : Relative permittivity of Si = 11.7]

[8 + 12 marks]

Sol^n

(i)

$$n = N_D + p \quad \text{[From charge neutrality]}$$

$$= N_D + \frac{n_i^2}{n} \quad \left[np = n_i^2 \text{ Mass action law}\right]$$

$$N_D = n - \frac{n_i^2}{n}$$

$$(n_i)_{max} = \frac{5}{100} n = \frac{n}{20}$$

$$\therefore N_{D\,min} = 20\, n_{i\,max} - \frac{n_{i\,max}^2}{20\, n_{i\,max}}$$

$$= 20\, n_{i\,max} - \frac{n_{i\,max}}{20}$$

$$N_{D\,min} = \frac{399}{20} n_{i\,max}$$

$$= \frac{399}{20} \times 3.20 \times 10^{14}$$

$$\left[N_{D\,min} = 63.84 \times 10^{14} \ cm^{-3} \right]$$

ii) $$W = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_R+V_{bi})}$$

p^+n junction $\Rightarrow N_A >> N_D$

$$\therefore W = \sqrt{\frac{2\varepsilon}{qN_D}(V_R+V_{bi})}$$

$$C' = \frac{\varepsilon}{W} = \frac{\varepsilon}{\sqrt{\frac{2\varepsilon}{qN_D}(V_R+V_{bi})}}$$

$$\Rightarrow \left[\frac{1}{C'}\right]^2 = \frac{2\varepsilon(V_R+V_{bi})}{qN_D\,\varepsilon^2}$$

$$= \frac{2}{qN_D\varepsilon}(V_R+V_{bi})$$

$$\left[\frac{1}{C'}\right]^2 = \left(\frac{2}{qN_D\varepsilon}\right)V_R + \frac{2}{qN_D\varepsilon}V_{bi}$$

$V_{bi} = 0.855$ V

$$\text{Slope} = \frac{2}{qN_D\varepsilon} = 1.32 \times 10^{15}$$

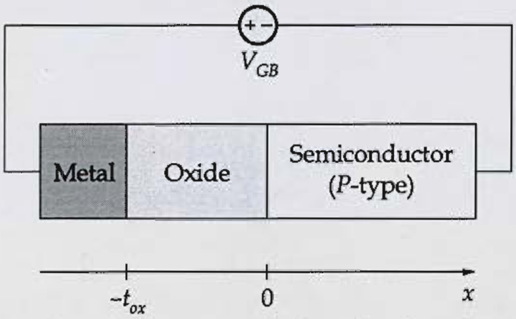
$$\Rightarrow N_D = \frac{2}{1.6\times10^{-19} \times 11.7\times8.854\times10^{-14} \times 1.32\times10^{15}}$$

$$N_d = \frac{2}{218.78 \times 10^{-18}}$$

$$N_d = 9.14 \times 10^{15}\ cm^{-3}$$

10 + 2

Q.6 (c) Consider a MOS structure shown below:



The oxide thickness, t_{ox} = 50 nm and the doping level in the p-type substrate is $N_a = 10^{16}$ cm^{-3}. Assume, intrinsic carrier concentration of semiconductor, $n_i = 10^{10}/\text{cm}^3$, thermal voltage, V_T = 26 mV, $\in_{oxide} = 3.45 \times 10^{-13}$ F/cm, $\in_{si} = 1.05 \times 10^{-12}$ F/cm. Calculate the hole concentration, p at the oxide-semiconductor interface (i.e., $x = 0$) under the following conditions:

(i) At flatband.

(ii) At threshold.

(iii) At a condition in which the potential build up from the quasi-neutral body of semiconductor to $x = 0$ is 0.5 V.

(iv) At a condition when the capacitance per unit area of the MOS structure is 50 nF/cm^2.

[20 marks]

Soln

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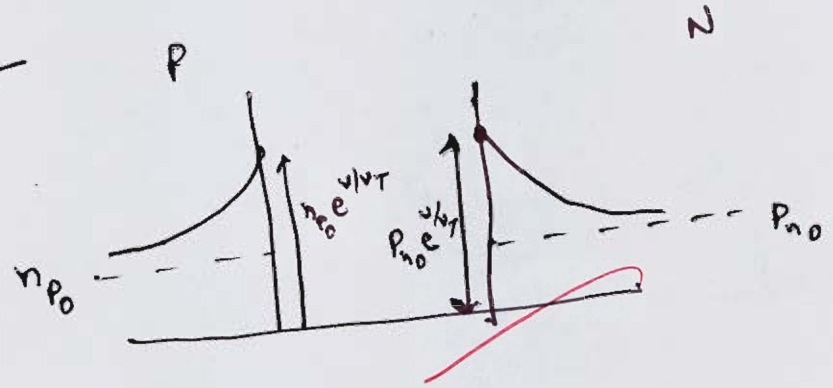
Do not write in this margin

Q.7 (a) Show that the ratio of hole diffusion current to electron diffusion current crossing a *p*-*n* junction is given by, $\frac{I_{pn}(0)}{I_{np}(0)} = \left(\frac{\sigma_p}{\sigma_n}\right) \times \left(\frac{L_n}{L_p}\right)$ where σ_p, σ_n are the conductivities and L_n, L_p are diffusion lengths of '*p*' and '*n*' regions respectively. Assume the junction is located at $x = 0$ and neglect the depletion layer width.

[20 marks]

Soln



Hole current :

$$P_n(x) = P_{n_0} + P_{n_0}\left(e^{V/V_T} - 1\right) e^{-x/L_P}$$

$$I_{pn}(0) = -qD_pA \frac{dP_n}{dx} = \frac{qAD_P P_{n_0}\left(e^{V/V_T} - 1\right)}{L_P}$$

Similarly,

Electron current

$$I_{np}(0) = \frac{qAD_n n_{p_0}\left(e^{V/V_T} - 1\right)}{L_n}$$

$$\frac{I_{pn}(0)}{I_{np}(0)} = \frac{D_P P_{n_0} L_n}{L_P \times D_n \cdot n_{p_0}}$$

$$P_{n_0} = \frac{n_i^2}{N_D} \quad \& \quad n_{p_0} = \frac{n_i^2}{N_A}$$

$$\therefore \frac{I_{pn}(0)}{I_{np}(0)} = \frac{D_P}{L_P} \frac{L_n}{D_n} \cdot \frac{N_A}{N_D}$$

From Eienstien relation

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T$$

$$\Rightarrow \frac{D_p}{D_n} = \frac{\mu_p}{\mu_n}$$

$$\therefore \frac{I_{pn}(0)}{I_{np}(0)} = \frac{\mu_p}{\mu_n} \frac{L_n}{L_p} \frac{N_A}{N_D}$$

Conductivity, $\sigma_p = N_A q \mu_p$

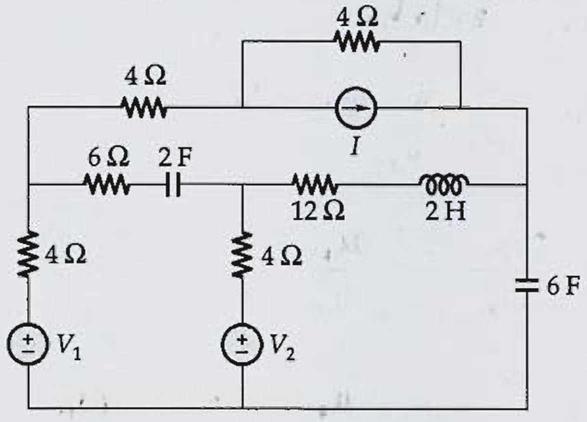
$$\sigma_n = N_D q \mu_n \Rightarrow \frac{\sigma_p}{\sigma_n} = \frac{N_A \mu_p}{N_D \mu_n}$$

$$\therefore \frac{I_{pn}(0)}{I_{np}(0)} = \frac{\mu_p}{\mu_n} \times \frac{L_n}{L_p} \times \frac{\sigma_p}{\sigma_n} \frac{\mu_n}{\mu_p}$$

$$\left[\frac{I_{pn}(0)}{I_{np}(0)} = \frac{\sigma_p}{\sigma_n} \times \frac{L_n}{L_p} \right]$$

16

Q.7 (b) For the network shown in figure, draw the oriented graph and compute.



(i) Complete incidence matrix and reduced incidence matrix.

(ii) Tie set matrix.

(iii) f-cut set matrix.

[20 marks]

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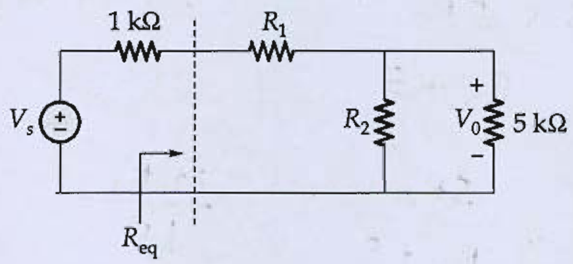
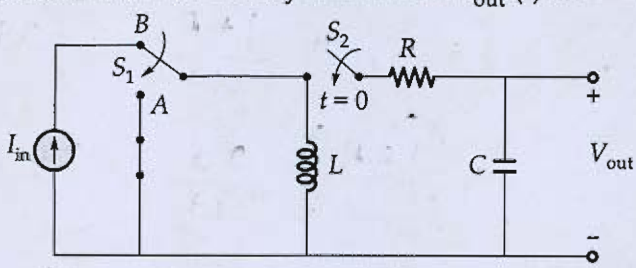
Q.7 (c) (i) In a certain application, the circuit shown below must be designed to meet these two criteria:

1. $\frac{V_0}{V_s} = 0.05$ 2. $R_{eq} = 39\ k\Omega$

If the load resistor 5 kΩ is fixed, find R_1 and R_2 to meet the criteria.



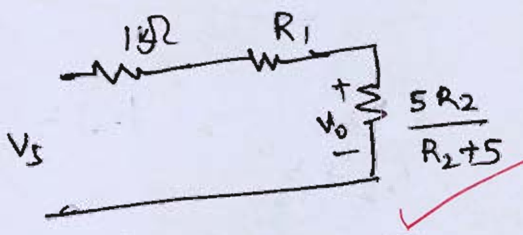
(ii) In the circuit shown below, $L = 0.5$ H, $C = 0.75$ F, $R = 3\ \Omega$ and $I_{in}(t) = 12$A (DC) for all time. Suppose that switch S_1 has been in position B for a very long time and switch S_2 has been open for all time. At time $t = 0$ switch S_1 moves to position A and switch S_2 closes instantaneously. Calculate $V_{out}(t)$ at $t = 1.5$ seconds if $V_{out}(0^-) = 0$



[10 + 10 marks]

Sol^n

(i) $R_{eq} = R_1 + \frac{5R_2}{R_2+5}$ [R_2 & R_1 in kΩ]



$$\frac{V_o}{V_s} = \frac{\left[\frac{5R_2}{R_2+5}\right]}{1+R_1+\frac{5R_2}{R_2+5}} = 0.05$$

$$\Rightarrow \frac{5R_2}{(R_2+5)(R_1+1)+5R_2} = 0.05$$

$$\frac{5R_2}{R_2+5} = 0.05(1+R_1) + \frac{5R_2}{R_2+5} \times 0.05$$

$$0.95 \times \frac{5R_2}{R_2+5} = 0.05(1+R_1)$$

$$\frac{5R_2}{R_2+5} = \frac{1+R_1}{19} \quad \text{—(i)}$$

Given $R_{eq} = 39\ k\Omega$

$$\therefore\ 1+R_1 + \frac{1+R_1}{19} = 39$$

$$(1+R_1)\frac{20}{19} = 39$$

$$1+R_1 = \frac{39 \times 19}{20}$$

$$= 37.05$$

8

$$\Rightarrow \boxed{R_1 = 36.05\ k\Omega}$$

$$\frac{5R_2}{R_2+5} = 1.95 \quad [\text{From i})$$

$$5R_2 = 1.95R_2 + 9.75$$

$$3.05\ R_2 = 9.75$$

$$\boxed{R_2 = 3.196\ k\Omega}$$

Q.8 (a) **(i)** In a very long p-type Si bar with cross-sectional area = 1 cm^2 and $N_A = 10^{17}$ cm^{-3}, we inject holes such that the steady state excess hole concentration is 3×10^{16} cm^{-3} at $x = 0$. What is the steady state separation between E_i and E_{F_p} at $x = 500Å$?
[Assume that $\mu_p = 500$ $cm^2/V\text{-}s$ and $\tau_p = 10^{-10}$ s, $n_i = 1.5 \times 10^{10}$ cm^{-3}]

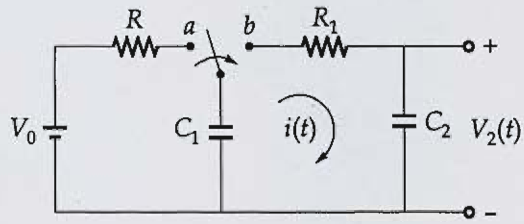
(ii) Assume that an n-type semiconductor is uniformly illuminated, producing a uniform excess generation rate g'.

Show that in steady state the change in the semiconductor conductivity is given by,

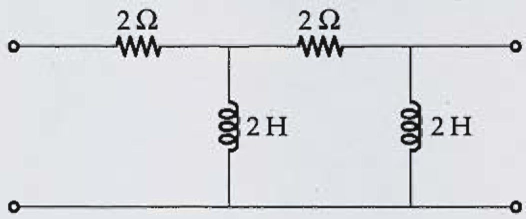
$\Delta\sigma = q(\mu_n + \mu_p)\, \tau_{p0}\, g'$

[12 + 8 marks]

Q.8 (b) (i) The switch is moved from the position a to b at $t = 0$, having been in the position a for a long time before $t = 0$. The capacitor C_2 is uncharged at $t = 0$. Find $i(t)$ and $V_2(t)$ for $t > 0$.



(ii) For the ladder network below, determine the h parameters in the s domain.



[10 + 10 marks]

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Q.8 (c) (i) Assume the base transit time of a BJT is 100 ps and carriers cross the 1.2 μm base-collector space charge region at a speed of 10^7 cm/s. The emitter-base junction charging time is 25 ps and the collector capacitance and resistance are 0.1 pF and 10 Ω respectively. Determine the cut-off frequency of the BJT.

(ii) An npn silicon transistor is biased in the inverse active mode with V_{BE} = – 3 V and V_{BC} = 0.6 V. The doping concentrations are $N_E = 10^{18}$ cm^{-3}; $N_B = 10^{17}$ cm^{-3}, and $N_C = 10^{16}$ cm^{-3}. Other parameters are x_B = 1 μm, $\tau_{E0} = \tau_{B0} = \tau_{C0} = 2 \times 10^{-7}$ s, D_E = 10 cm^2/s, D_B = 20 cm^2/s, D_C = 15 cm^2/s and area $A = 10^{-3}$ cm^2. Calculate the collector and emitter currents (Neglect geometry factors and assume the recombination factor is unity) (Assume, $n_i = 1.5 \times 10^{10}$ cm^{-3}, V_t = 0.0259 V, τ = carrier life time and D = diffusion coefficient.)

[10 + 10 marks]

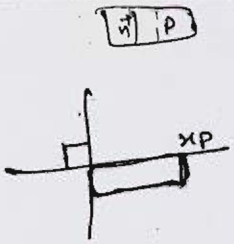
OOOO

Space for Rough Work

Space for Rough Work

Space for Rough Work

Space for Rough Work



$$W = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A}\right)(V_R + V_D)}$$

$$V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$V_{bi} = V_T \ln \frac{N_A}{n_i^2} + V_T \ln N_d$$

$$\frac{4+9}{24}$$

$$\frac{\frac{11}{4} \times 3}{3 + \frac{11}{4}} = \frac{33}{12+11}$$

$$= \frac{33}{23} + 2$$

$$\frac{79}{23}$$