1

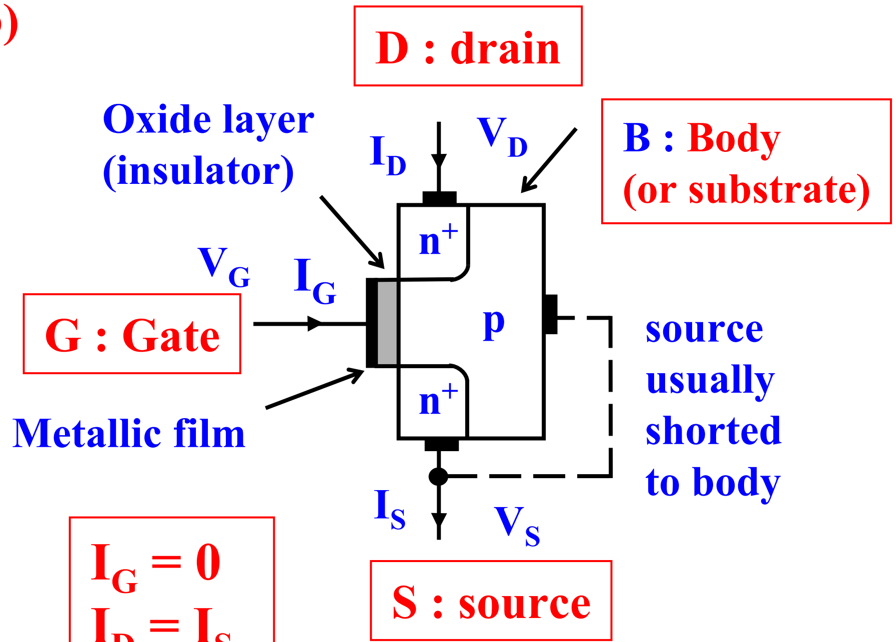
(a) Name two advantages of MOSFET. (b) Draw the cross sectional diagram for an enhancement NMOSFET and describe very briefly the structure. Are IG = 0 and ID = IS? (15)

(a)

**small size (scaled down easily) and low power consumption.**

(4)

(b)




$I_G = 0$
$I_D = I_S$

(1)

An NMOSFET consists of a **metal gate** insulated from a **p-type semiconductor** substrate (or body) by an insulating layer of **silicon dioxide.** On either side of the gate there are **n type** regions forming the **drain and source.**

(10)

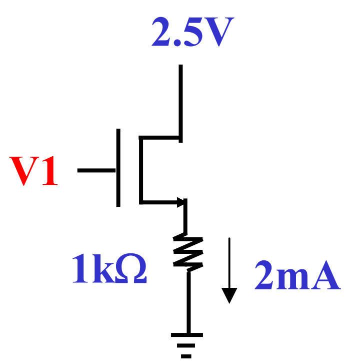
(16)

**1**

In the circuit, find V1 . Show clearly your reasons . (16)

Given that VT = 1V , K = 2 mA/V2.
At triode region , VGS ≥ VT , VDS < VGS - VT , ID = 2K(VGS –VT)VDS – KVDS2
At saturation region , VGS ≥ VT , VDS ≥ VGS - VT , ID = K[(VGS –VT)2 ]

(c)




$V_{GS}$ = V1 - 2 $V_{DS}$ = 0.5V

NMOS may be triode since $V_{DS} \sim 0$ (4)

$$\therefore \mathbf{I} = 2\mathbf{K}[(\mathbf{V}_{GS} - \mathbf{V}_T)\mathbf{V}_{DS} - \frac{\mathbf{V}_{DS}{}^2}{2}]$$

$$\therefore 2\mathbf{mA} = 2*2[(\mathbf{V}1 - 2 - 1)*0.5 - \frac{0.5^2}{2}]$$

$$\therefore \mathbf{V}1 = (\frac{2\mathbf{mA}}{4} + 0.125)*2 + 3 = 4.25\mathbf{V}$$

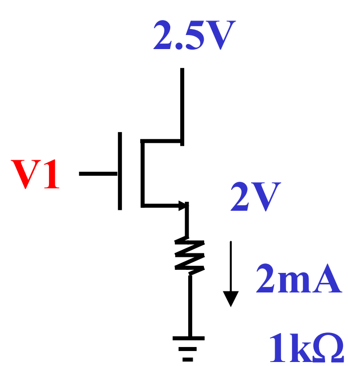
(8)

Hence NMOS is triode since
1. $V_{GS} > V_T$ 2.25 > 1
2. $V_{DS} < V_{GS} - V_T$ 0.5 < 2.25 - 1

(4)

---

(c)




$$\therefore \mathbf{I} = 2\mathbf{K}[(\mathbf{V}_{GS} - \mathbf{V}_T)\mathbf{V}_{DS} - \frac{\mathbf{V}_{DS}{}^2}{2}]$$

$$= 2*2\mathbf{m}[(4.25 - 2 - 1)*0.5 - \frac{0.5^2}{2}] = 2\mathbf{mA}$$

**(18)**

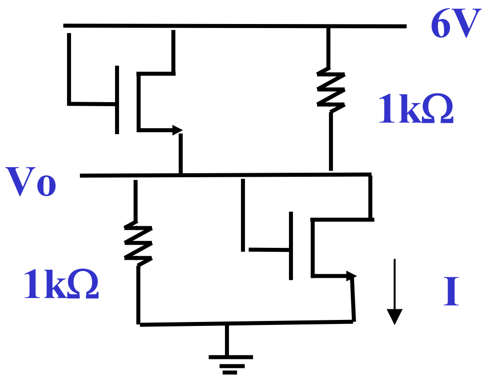
**2** Find I . Show clearly your reasons. (18)

Given the NMOS are identical,

$V_T = 1V$, $K = 0.25m\ A/V^2$ .

At triode region , VGS ≥ VT , VDS < VGS - VT , ID = 2K(VGS –VT)VDS – KVDS2

At saturation region , VGS ≥ VT , VDS ≥ VGS - VT , ID = K[(VGS –VT)2 ]




Assume 2 NMOS are in saturation and use KCL

**(4)**

$$\therefore I_D = K\,(V_{GS} - V_T)^2$$

$$\therefore 0.25m * (6 - Vo - 1)^2 + \frac{6 - Vo}{1k\Omega} = 0.25m * (Vo - 1)^2 + \frac{Vo}{1k\Omega}$$

**(4)**

From symmetry, Vo = 3V **(5)**

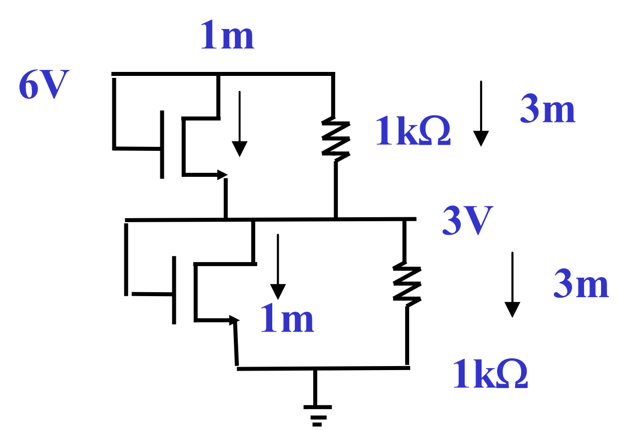
$$\therefore I = 0.25m * (6 - 3 - 1)^2 = 1mA$$ **(2)**

$V_{GS1} = 3V$ $V_{DS1} = 3V$

$V_{GS2} = 3V$ $V_{DS2} = 3V$

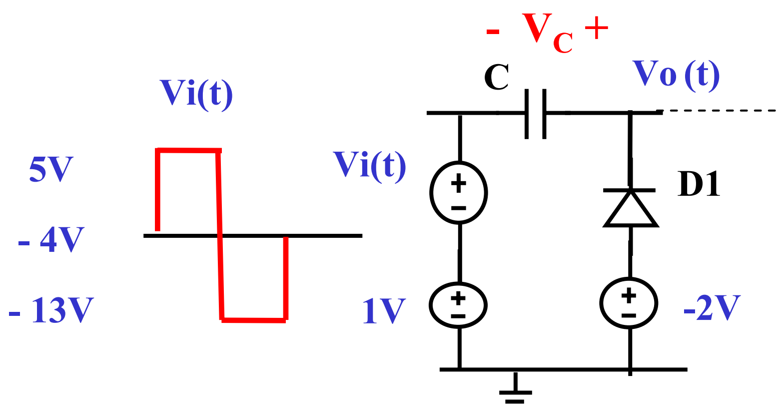
Hence NMOS is saturate since

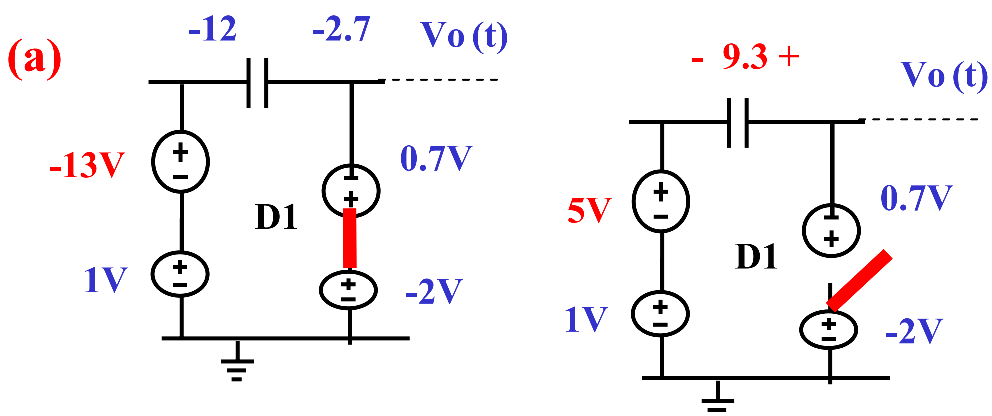
1. $V_{GS} > V_T$ $3 > 1$
2. $V_{DS} > V_{GS} - V_T$ $3 > 3 - 1$ **(4)**



**3** In the diode circuit, find Vc . Hence sketch and label clearly Vo(t) .

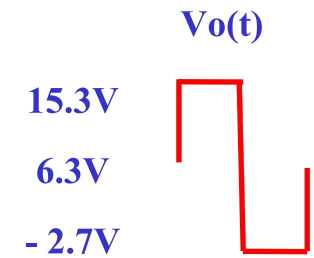
**(a)** D1 is an <u>offset diode</u> with VF = 0.7V . (17)



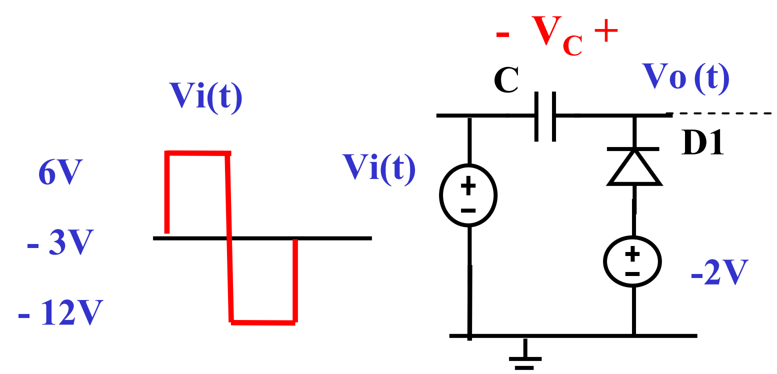

$V_C = 9.3V$ (11)

$\boxed{Vo = Vi + 1 + Vc = Vi + 10.3V}$ (3)




(3)

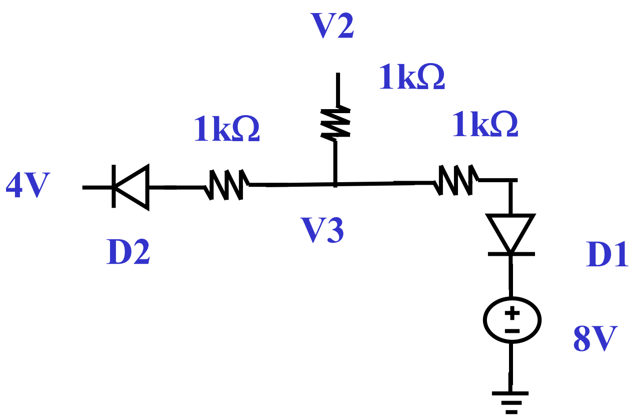
OR



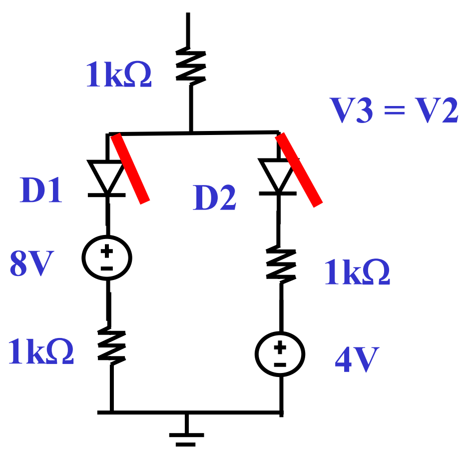

$\boxed{Vo = Vi + Vc = Vi + 9.3V}$ (3)

**3** In the ideal diode circuit, plot V3 versus V2 for $18V \geq V2 \geq 0V$. (24)

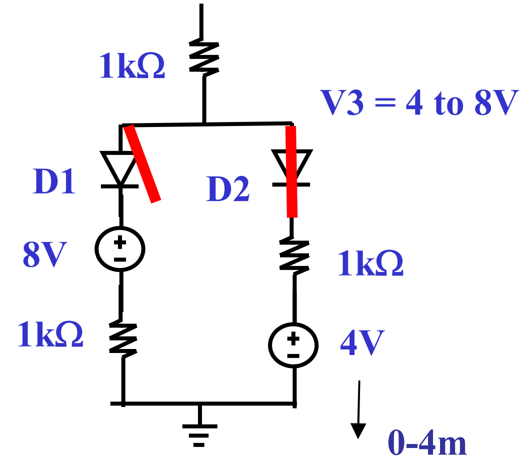
**(b)**



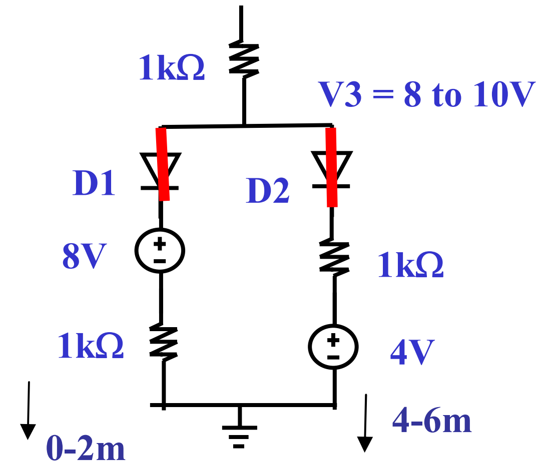

V2 = 0 to 4V

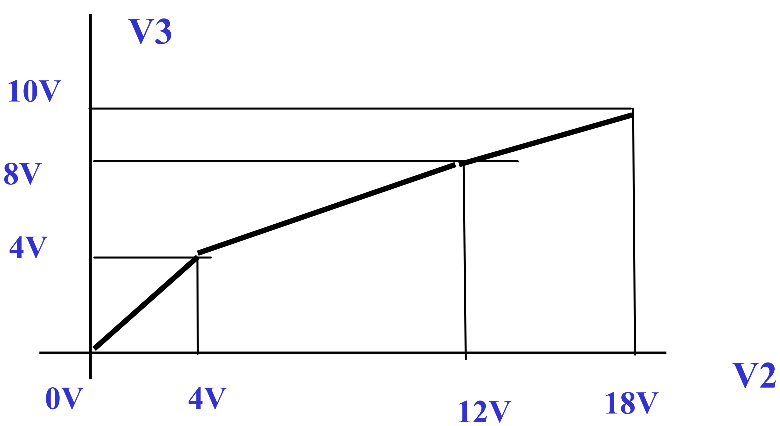



V2 = 4 to 12V




V2 = 12 to 18V




(8) (8) (8)

**4**

**(a) Find the model of the diode D1 at breakdown.**

**(b) Find I1 if R3 = 1kΩ, I2 = 5mA, R1 = R2 = 4kΩ, V1 = 3V.**

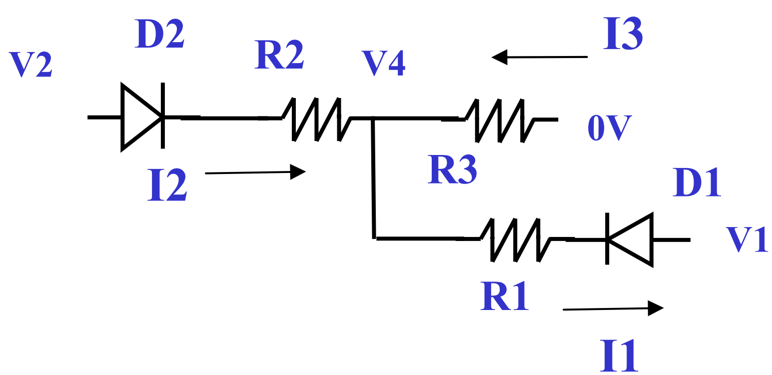
**(c) Find V2 if V1 = 4.7V, R1 = R2 = 1kΩ, R3 = 2kΩ, I1 = -1mA, V4 = 3V.**

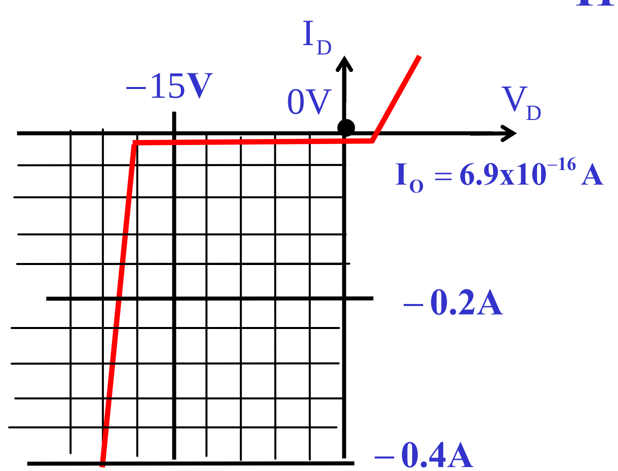
**Show clearly your reasons . (30)**

**Given that D1 and D2 are identical.**

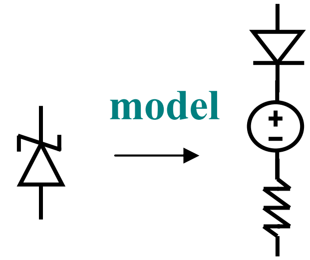
**Diode equation is** $I_D = I_O * [e^{\frac{V_D}{25mV}} - 1]$

**and the diode has the I-V curve as shown.**



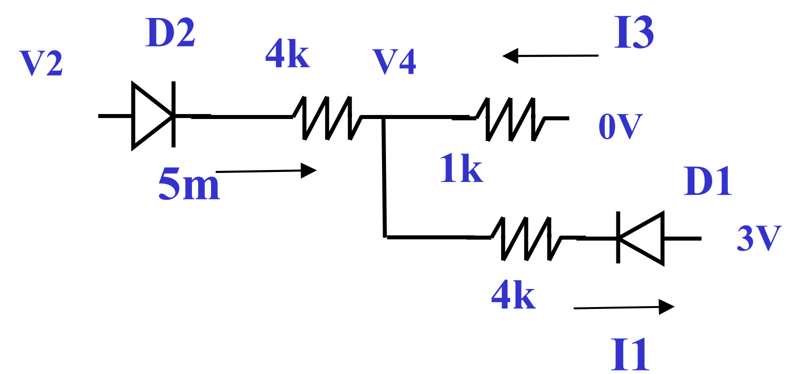

**(a)**




$V_{ZO} = 18V$ **(7)**

$r_Z = 3V/0.4A = 7.5\Omega$

**(b)**




**V4 = 5V > 3V**

**D1 is OFF** **(5)**

**$I1 = Io = 6.9x10^{-16}A$** **(3)**

$$\frac{3 - v4}{4k} + 5m = \frac{v4}{1k}$$

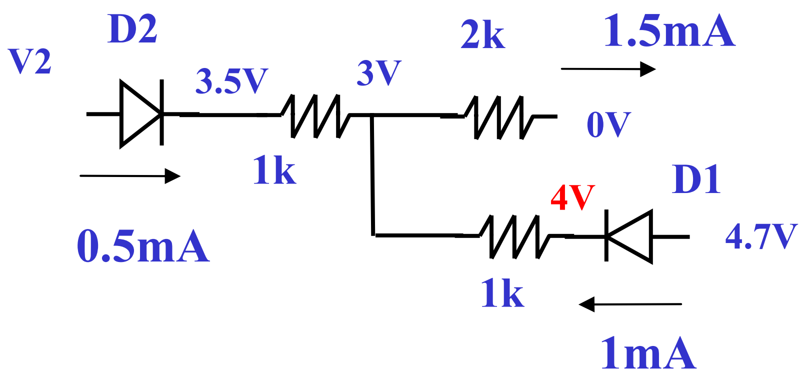
$$3 - v4 + 20 = 4v4$$

$$v4 = 4.6V$$

**Use KCL and D1 is OFF**

**4**

**(c)**




$\therefore$ I2 = 0.5mA **(5)**

$$\therefore 0.5\text{mA} \cong I_O\left(e^{\frac{VD}{25\text{mV}}}\right)$$ **(2)**

$$\therefore VD = 25\text{mV} * \log_e \frac{0.5\text{mA}}{6.9\text{x}10^{-19}\,\text{A}} \cong 682.7\text{mV}$$ **(5)**

$$\therefore V2 \cong 3.5 + 0.683 = 4.183\text{V}$$ **(3)**

**OR**

$$\therefore 1\text{mA} = I_O\left(e^{\frac{VD}{25\text{mV}}} - 1\right) \cong I_O\left(e^{\frac{700\text{mV}}{25\text{mV}}}\right)$$

$$\therefore 0.5\text{mA} \cong I_O\left(e^{\frac{VD}{25\text{mV}}}\right)$$

$$\therefore \log_e 2 = \frac{700\text{mV - VD}}{25\text{mV}}$$

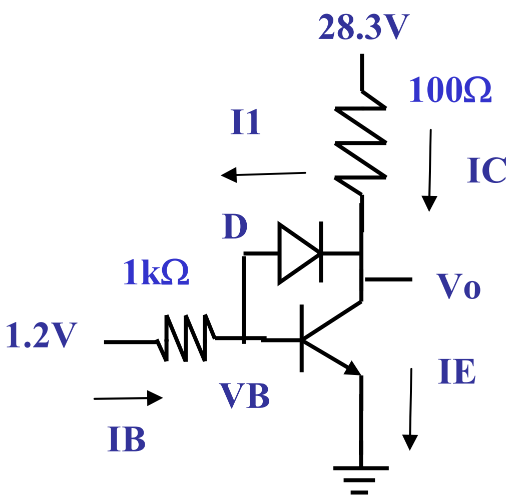
$$\therefore VD \cong 682.7\text{mV}$$

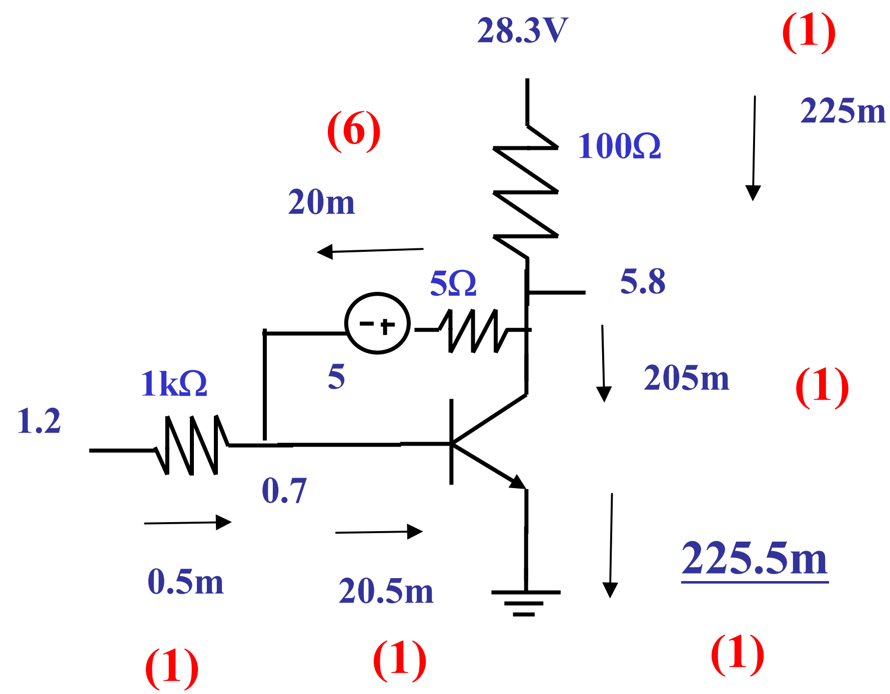
$$\therefore V2 \cong 3.5 + 0.683 = 4.183\text{V}$$

(18)

**5**

**Find IE. Given Vo = 5.8V.**
**Show clearly your reasons. For the BJT, given VBE(ON) = 0.7V, β = 10, VCESAT = 0.2V.**
**For the diode, the diode equation is** $I_D = I_O * [e^{\frac{V_D}{25mV}} - 1]$
**and Io =** $10^{-13}$**A. . In breakdown, Vzo = 5V, rz = 5Ω. (18)**




$\therefore$ VB = 0.7V (3)

D is breakdown since Vo = 5.8V (4)

**(40)**

**6**

(a) Name two III-V compound semiconductors.
(b) Find the conductivity of intrinsic (pure) Germanium (Ge). Find also the resistivity.
(c) The pure Ge is doped to n-type Ge with a dopant of $1x10^{22}$/m3. Find the conductivity. Find also the hole concentration (in atoms / m3 ).
(d) $5 \times 10^{20}$ / m3 indium atoms are used to dope the pure Si . Find the electron density n, hole density p , and conductivity σ . Is the doped Si n-Si or p-Si ?

Given that $\sigma = e(n\mu_n + p\mu_p)$ , $\rho = 1/\sigma$ , $np = n_i^2$ , $e = 1.6 \times 10^{-19}$ C
For Ge : $n_i = 2.4 \times 10^{19}/m^3$, $\mu_p = 0.19$ m²/Vs, $\mu_n = 0.39$ m²/Vs .
For Si : $n_i = 1.5 \times 10^{16}/m^3$, $\mu_p = 0.048$ m²/Vs, $\mu_n = 0.135$ m²/Vs .
Some atoms : group 3 (boron B, gallium Ga, indium In) ; group 5 (nitrogen N, phosphorus P, arsenic As) (40)

---

**(a)** III-V compound GaAs, InP etc **(4)**

**(b)** The conductivity of intrinsic (pure) Ge

$$\sigma_i = e(\mu_N n_i + \mu_P n_i) = en_i(\mu_P + \mu_N)$$
$$= 1.6x10^{-19} x 2.4x10^{19} x(0.19 + 0.39) \cong 2.227 / \Omega m$$ **(7)**

$$\rho_i = \frac{1}{\sigma_i} \cong \frac{1}{2.227} \cong 0.45 \Omega m$$ **(4)**

**(b)**

$$\therefore \sigma_N = e(\mu_P p + \mu_N n) \cong e(\mu_N n)$$
$$= 1.6x10^{-19} * (0.39 * 1x10^{22}) \cong 624 / \Omega m$$ **(7)**

$$\therefore p = \frac{n_i^2}{n} = \frac{(2.4x10^{19})^2}{1x10^{22}}$$
$$\cong 5.76x10^{16} \text{ holes} / m^3$$ **(6)**

**(c)** P-type **(2)**

$$\therefore p \cong 5x10^{20} \text{ holes} / m^3$$ **(4)**

$$\therefore n = \frac{n_i^2}{p} = \frac{(1.5x10^{16})^2}{5x10^{20}}$$
$$\cong 4.5x10^{11} \text{ electrons} / m^3$$ **(6)**

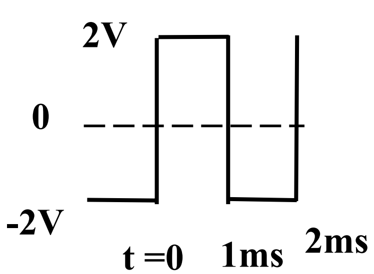
---

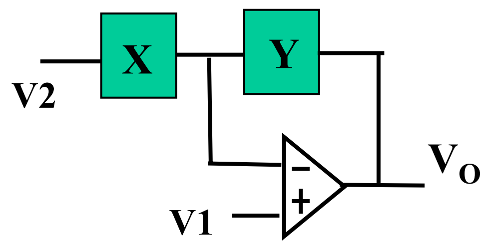
$$\therefore \sigma_P = e(\mu_P p + \mu_N n) \cong e(\mu_P p)$$
$$= 1.6x10^{-19} * 0.048 * 5x10^{20}$$
$$= 3.84 / \Omega m$$

**(21)**

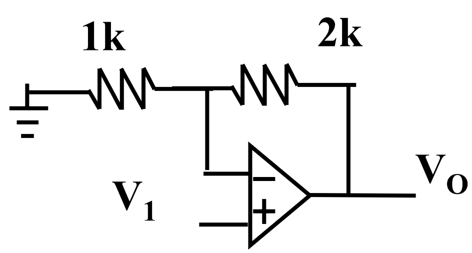
**7**

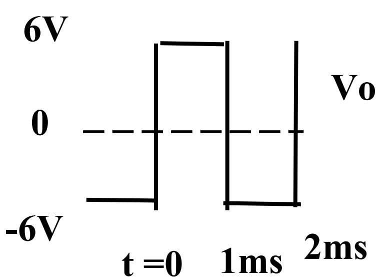
(a) If X = 1kΩ, Y = 2kΩ, V2 = 0V, V1 = given waveform, draw the waveform of Vo .
(b) If Y = 1µF, X = 1kΩ, V1 = 0, V2 = given waveform . Derive the equation for the output voltage $V_O$ , and hence draw the waveform of $V_O$ . Given Vo(0) = 0V.
Assume the op amp is ideal. (21)




**(a)**

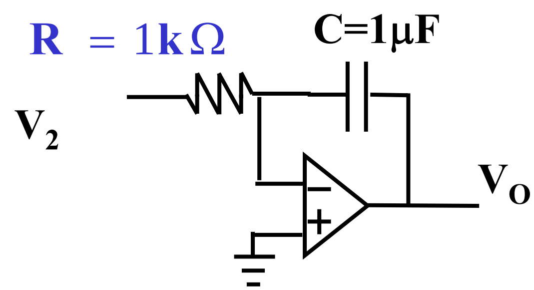



**Vo/V1 = 1+2k/1k = 3**

**(8)**

**(b)**

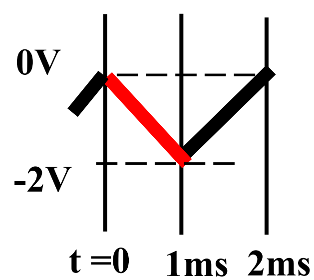



$$\frac{V2}{R} = C\frac{d(0-Vo)}{dt}$$

$$\frac{dVo}{dt} = \frac{-V2}{CR} = \frac{-2V}{1ms}$$

$$\text{given } Vo(0) = 0V$$

**(8)**

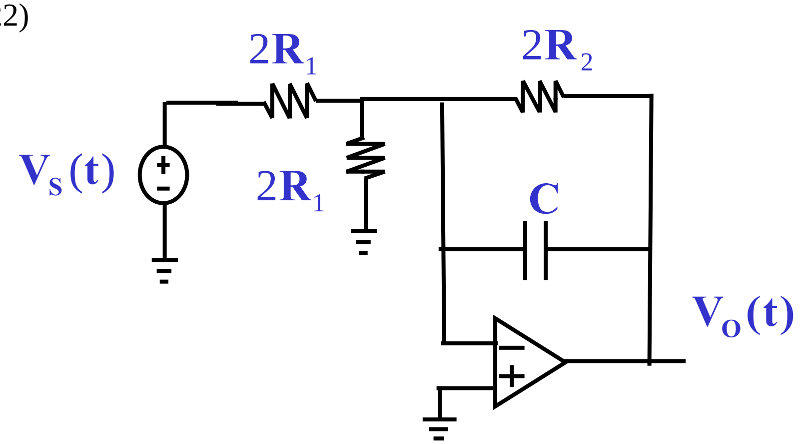


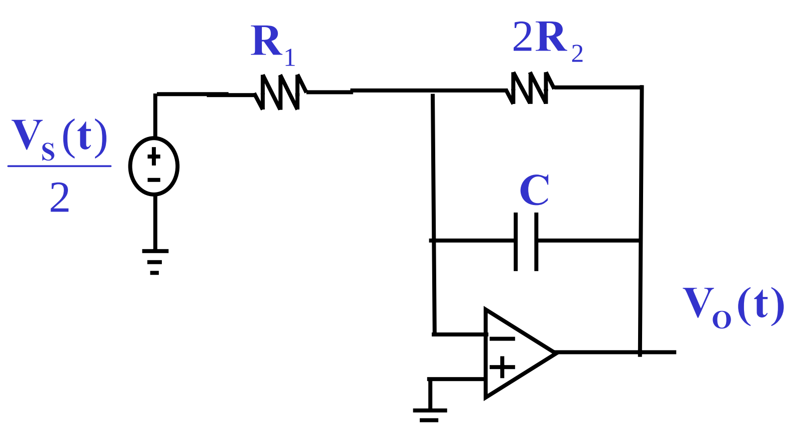

**(5)**

**8**

(a) Find the complex transfer function G (= Vo / Vs ) in terms of R1, C, R2 and jw .

(b) If R1 = 2kΩ, R2 = 5kΩ , C = 0.01uF, plot the magnitude of G ( |G| ) versus ω . Show clearly the value of |G| when ω = 0 , ω = ∞ , and ω = ωO (cut-off frequency) in your plot . Find also ωO . Assume op amp is ideal.
(22)



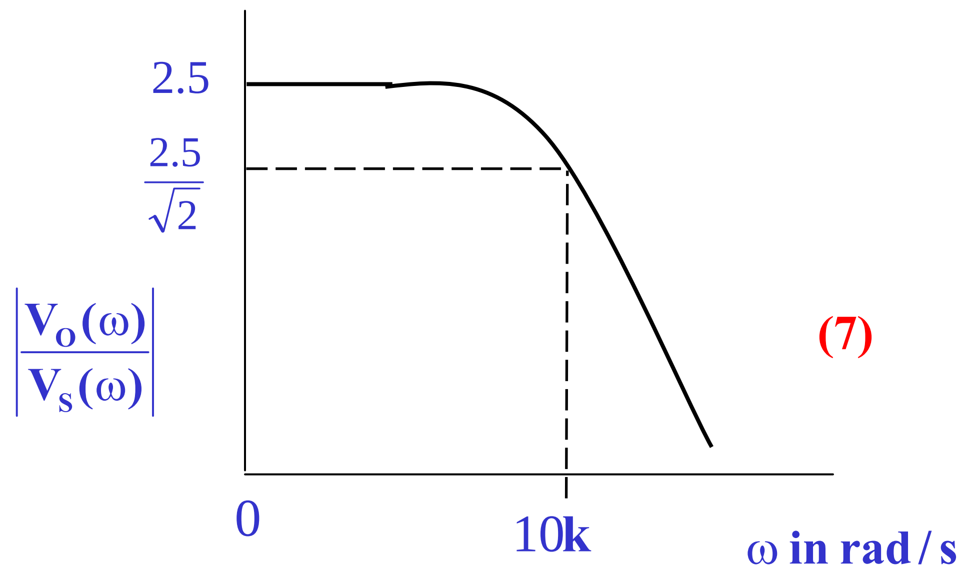

$$\frac{V_O}{0.5V_S} = -\frac{Z_2}{Z_1} = -\frac{2R_2 // \frac{1}{j\omega C}}{R_1}$$

$$\frac{V_O}{V_S} = -\frac{2R_2 * \frac{1}{j\omega C}}{2R_1\left(2R_2 + \frac{1}{j\omega C}\right)} = -\frac{2R_2}{2R_1} * \frac{1}{1 + j\omega C * 2R_2}$$

$$= -\frac{R_2}{R_1} * \frac{1}{1 + j\frac{\omega}{\omega_O}}$$ **(10)**

$$2\omega CR2 = 1$$

$$\omega = \omega_O = \frac{1}{2CR2} = \frac{1}{2*0.01u*5k} = 10\text{krad/s}$$ **(5)**




**(7)**

(20)

**9**

In an ideal op amp filter circuit, the complex transfer function G (= $V_O / V_S$ ) is given as. $\dfrac{-20}{1-\dfrac{2\mathbf{j}}{\boldsymbol{\omega}\mathbf{CR}}}$

(a) If $\mathbf{V_O}(\mathbf{t}) = \dfrac{-10}{\sqrt{17}}\cos(200\mathbf{kt}+66^o)\ \mathbf{V}$ , find Vs(t) .

(b) Find the cut-off frequency ω = ωO. Is the ideal op amp circuit a low pass filter?

Given that 1/CR = 400krad/s . (20)

**(a)**

$$\mathbf{G} = \frac{-20}{1-2\mathbf{j}/200\mathbf{k}*\mathbf{CR}} = \frac{-20}{1-4\mathbf{j}} = \frac{-20}{\sqrt{17}\angle -76^o} \quad \textbf{(5)}$$

$$\therefore \mathbf{V_S} = \frac{-10}{\sqrt{17}}\angle 66^o / \frac{-20}{\sqrt{17}}\angle 76^o = 0.5\angle -10^o\,\mathbf{V} \quad \textbf{(5)}$$

$$\therefore \mathbf{V_S}(\mathbf{t}) = 0.5\cos(200\mathbf{kt}-10^o)\mathbf{V} \quad \textbf{(3)}$$

**Circuit is a high pass filter** **(3)**

**(b)**

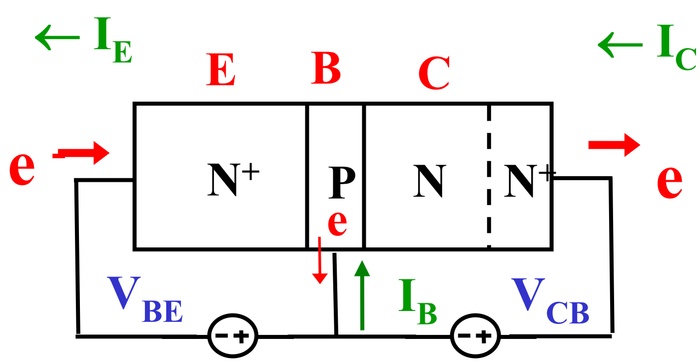
$$\mathbf{G} = \frac{-20}{1-\mathbf{j}} \Rightarrow 2/\boldsymbol{\omega}\mathbf{CR} = 1$$

$$\omega = \omega_O = \frac{2}{\mathbf{CR}} = 800\mathbf{krad/s} \quad \textbf{(4)}$$

**10**

**Draw the cross sectional structure of a NPN BJT transistor operated in the amplifier mode. Describe the movement of electrons, the designs in the emitter/base/collector, and explain briefly the equation IE $\approx$ IC / $\alpha$ . Given $I_C \cong \beta I_B$, find $\alpha$ if $\beta = 200$. (17)**

**(a)**




**(4)**

1. **EB Junction is a forward bias (on) diode and BC is reverse bias (off) diode**

2. **E is very heavily doped (N + for NPN). E has many electrons,**

3. **B is very thin. So most electrons injected from E (to B) are attracted to C and**

$$I_C \cong \alpha I_E$$

**(7)**

$$I_E \cong \frac{I_C}{\alpha} = I_B + I_C = \frac{I_C}{\beta} + I_C$$

$$\text{hence } \frac{1}{\alpha} = \frac{1}{\beta} + 1$$

$$\beta = \frac{\alpha}{1-\alpha}$$

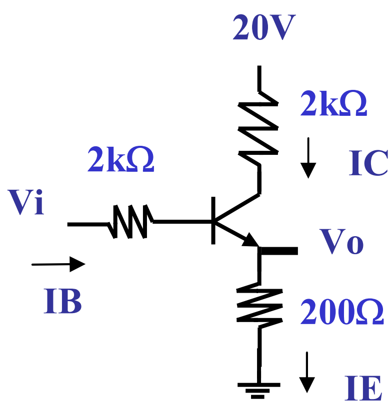
$$\alpha = \frac{\beta}{\beta+1} = \frac{200}{201}$$

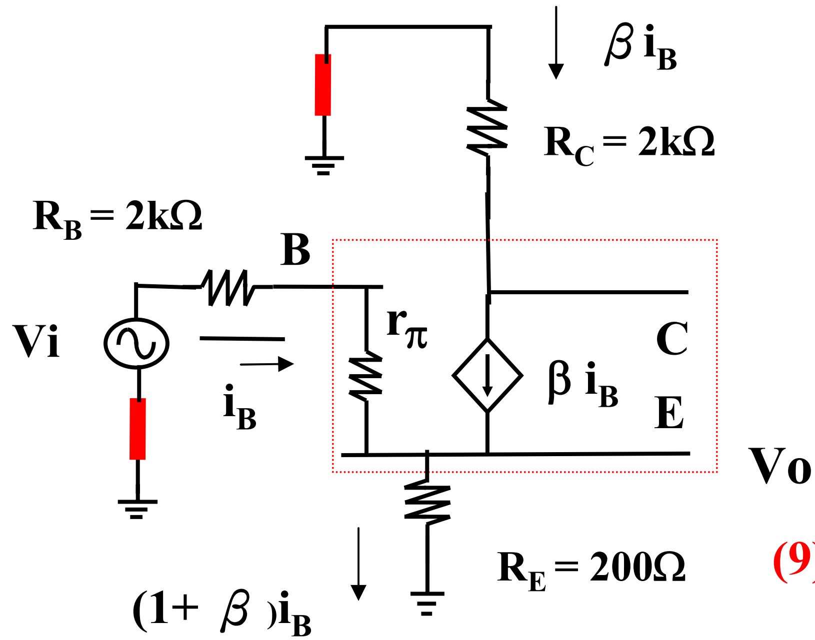
**(6)**

**11**

**Draw the small signal (AC) equivalent circuit of the BJT amplifier and find the voltage gain Av ( = Vo / Vi ).**

**Given $r\pi = 10\Omega$, $ro = \infty\Omega$, $\beta = 100$, and $V_{CESAT} = 0.2V$, $V_{BE(ON)} = 0.7V$. (19)**




(9)

$$\therefore Av = \frac{Vo}{Vi} = \frac{(1+\beta)i_B R_E}{i_B(R_B + r_\pi) + (1+\beta)i_B R_E} \quad (6)$$

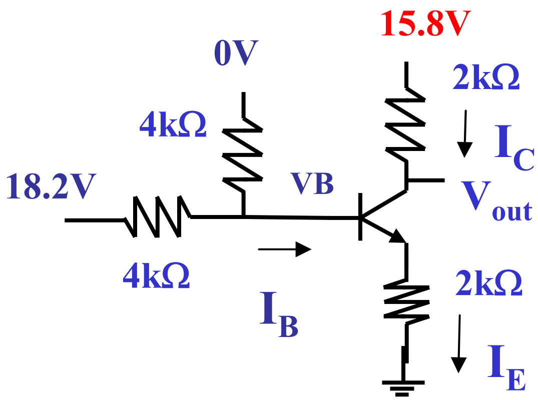
$$= \frac{(1+\beta)R_E}{R_B + r_\pi + (1+\beta)R_E}$$

$$= \frac{101 * 200\Omega}{2010 + 101 * 200\Omega} \cong 0.91 \quad (4)$$

(20)

**12** If IB = 0.2mA, find IC/IB.

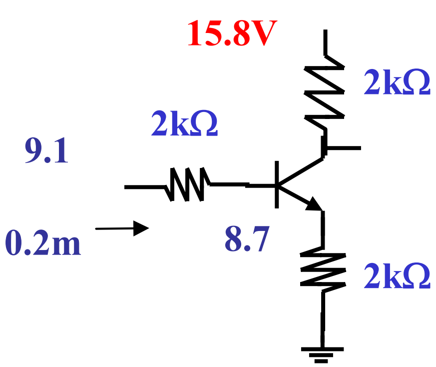
Show clearly your reasons. For the BJT, given
$V_{BE(ON)} = 0.7V$, $\beta = 100$, $V_{CESAT} = 0.2V$. (20)




**(a)**

when $V_{CE} = V_{CESAT}$

$$I_C \cong I_E \cong \frac{15.8V - 0.2V}{4k\Omega} = 3.9mA$$




Now IB = 0.2mA, VB = 8.7V, VE = 8V,

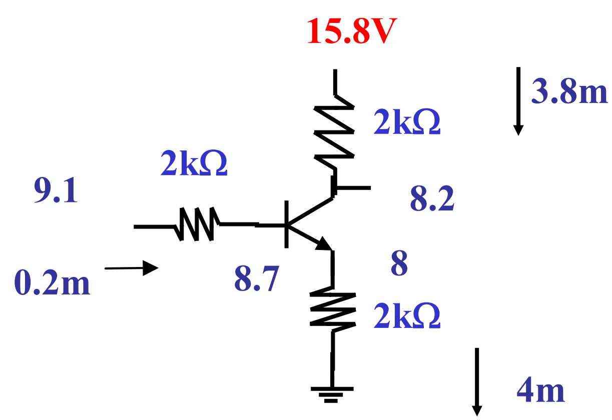
IE = 4mA, hence BJT is SAT

( OR IB ~ IC/ β ~ 0.04mA

But now IB ~ 0.2mA, hence BJT is SAT )

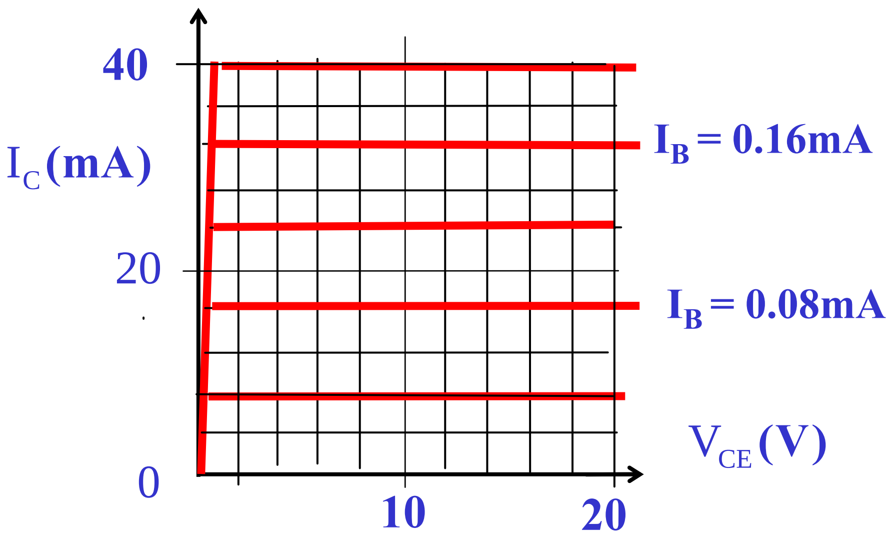
Hence Vout = 8.2V, Ic = 3.8mA **(17)**

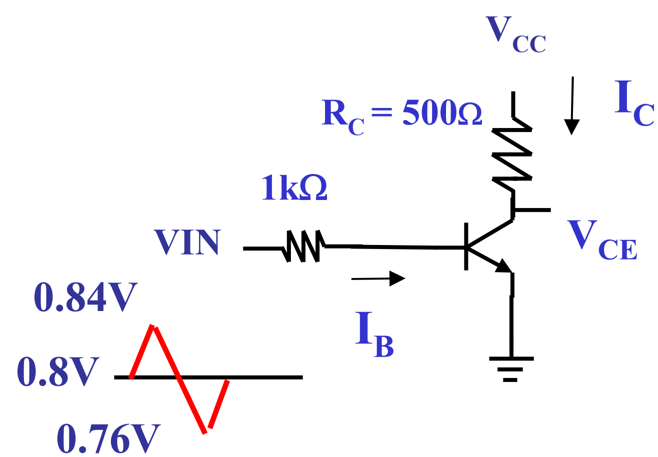
$$\therefore \beta' = \frac{I_C}{I_B} = \frac{3.8mA}{0.2mA} = 19$$ **(3)**



**13**

Given the BJT circuit below and the $I_C$ -$V_{CE}$ curve of the BJT.
Given the VB waveform and VCEQ = 10V. (a) Find VCC , draw the load line $V_{CE}$ = VCC – $I_C R_C$ and locate the Q point on the load line .
(b) Estimate the voltage gain (VCE / VIN) from the load line and IC -VCE curves . Show also on the load line the range of movement of the bias point . Draw and label also the waveform of VCE.
(c ) If VBE(ON) is changed from 0.7V to 0.62V, draw roughly and label the waveform of IC. (33)
For the BJT, given $V_{BE(ON)}$ = 0.7V , $V_{CESAT}$ = 0.2V .



**Draw load line, Draw Q point,**

**(a)**

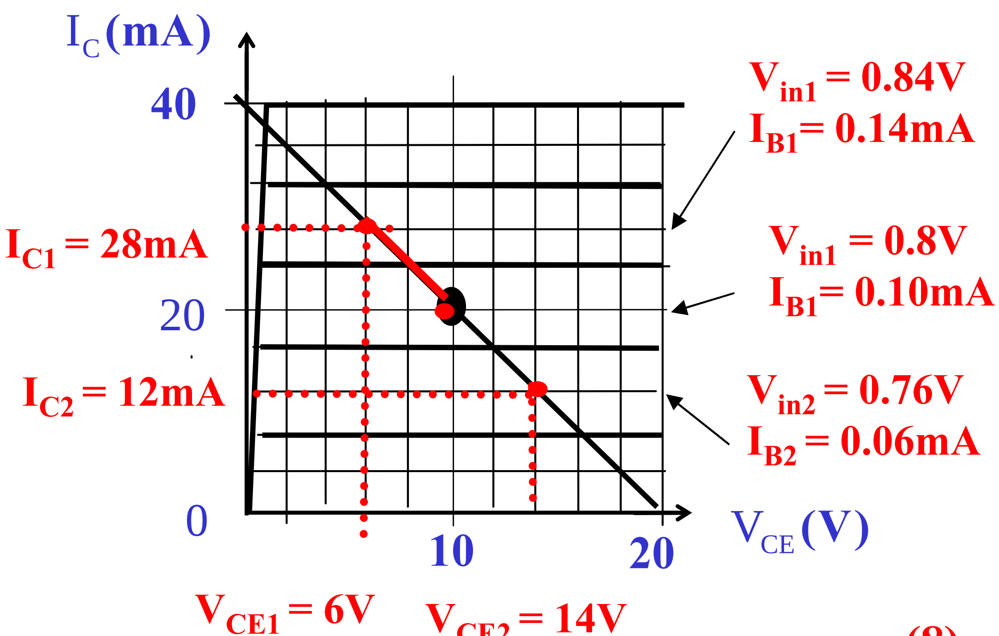
$$\therefore I_{BQ} = \frac{0.8V - 0.7V}{1k\Omega} = 0.1mA$$

$$\therefore I_{CQ} = 20mA$$

**(6)**

$$\therefore V_{CC} = 10V + 20mA * 500\Omega = 20V$$

**(4)**



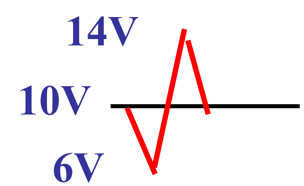

**(8)**

**(b)**

$$\text{voltage gain } A_v = \frac{v_{CE}}{v_B} = \frac{V_{CE2} - V_{CE1}}{V_{in2} - V_{in1}}$$

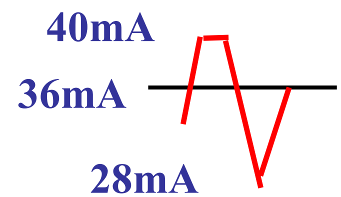
$$\cong \frac{14V - 6V}{0.76V - 0.84V} \cong -100$$

**(5)**




**(3)**

**If VBE(ON) is changed to 0.62V, Q point moves to IB = 0.18mA, IC = 36mA, IC waveform ~**




**(7)**