Lecture: 0

Integrated Electronics

PROF

Dr. Abhijit Mitra

office hour : Friday (11-12)

TF: Suhail Khan and Aafreen

Evaluation

Group2 Project : 10

2x quiz : 10

Mid sem : 20

End sem : 30

Lab : 20

Tut and simulation : 10

BOOK

Microelectronic circuits by A. sedra and K. smith 7th edition

GRADING : ?

FOCUS

understand analog elements and circuits using BJT & CMOS

LAB

LTSpice

PCB design

6 Labs

4 debugging slot

no midsem/endsem

lab viva/practical

PROJECT

3 topics will be given

Hardware based

Group of 2

the debugging slots will be for the project

EXAM

harder than quiz

bonus : 5% for 75% attendance in lectures

23 lectures

Project starts from week 7

Final Demo : 16th week

informed simulation (not surprise)

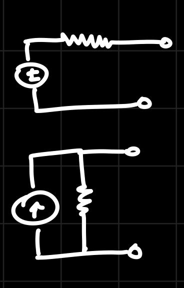
- lecture : 1

COURSE: Analog Electronics

⇒ Signals

→ contains info about of stuff in physical environment
eg: Temp, Pressure, Heat, Audio etc.
→ Devices are used to extract info from the environment
→ Signals can be processed to achieve the desired results. eg: amplification / compression / ...
→ Processed using electronic circuits.
→ Physical signals must be identically converted into an electronic signal using TRANSDUCERS
eg: microphones have pressure transducers
seismic transducers used for animal movement by NFR in remote areas

Voltage SRC → Thevenin →
Current SRC → Norton →



waves
↳ Amplitude
↳ Frequency
↳ Phase

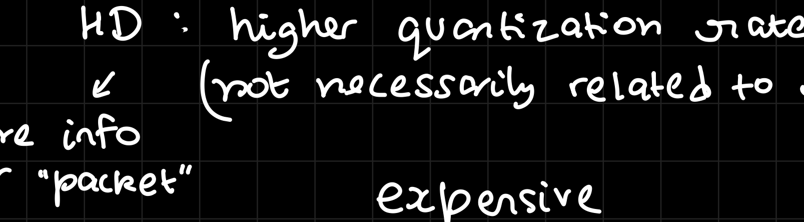
• FREQUENCY SPECTRUM OF SIGNALS

no. of frequencies in....
∿ sinusoidal signal → 1 at origin
⎍ rectangular signal → very high
⟋ sawtooth signal → very high

sampling → convert from analog to discrete

digital vs discrete
digital ↓ limited on the amplitude scale
discrete ↓ no limit on the set of amplitude it can achieve

Two level quantizer → snaps the value to either 0/1 depending if value is low/high
↳ not that useful

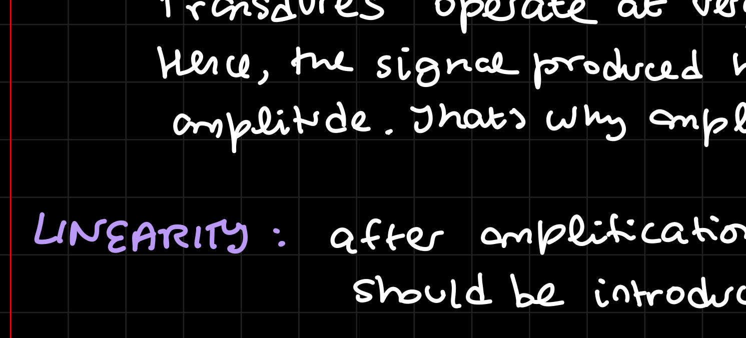


4 level quantizer → better resolution / precision

HD : higher quantization rate
(not necessarily related to sampling rate)
↙ more info per "packet"

expensive
↳ ckt design
↳ transportation from source to destination

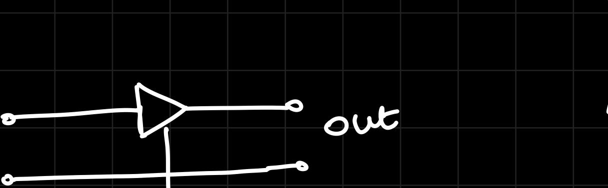
Conversion happens using A/D converter
analog → digital



⇒ Amplification

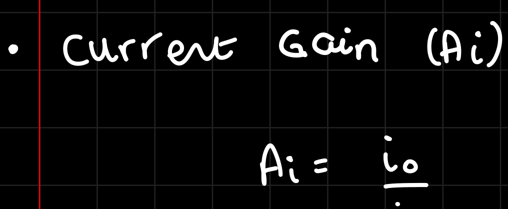
Transdures operate at very low power ~10μV. Hence, the signal produced has a very low amplitude. Thats why amplifiers are needed.

LINEARITY : after amplification, no distortion should be introduced



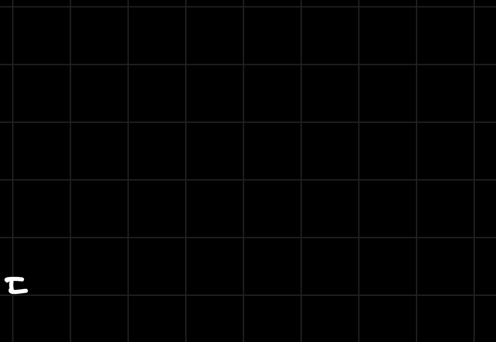
↳ not a good amplifier (non-linear)

* Two kind of Amps
↳ Voltage Amplifiers
↳ current Amplifiers
} ⇒ we also have power amplifiers
↳ substantial current gain
↳ moderate voltage gain



- Voltage Gain (A_v)

$$A_v = \frac{V_o}{V_i}$$



ideal linear amp

- Current Gain (A_i)

$$A_i = \frac{i_o}{i_i}$$

- Power Gain (A_p)

$$A_p = \frac{V_o i_o}{V_i i_i} = A_v A_I$$

→ Gain in dB (logarithmic scale)

only two operations : add/subtract
easier to operate on larger values

Volt gain in dB = $20 \log_{10} |A_v|$ (absolute value) — negative means phase shift signal hasn't attenuated

Current gain in dB = $20 \log_{10} |A_i|$

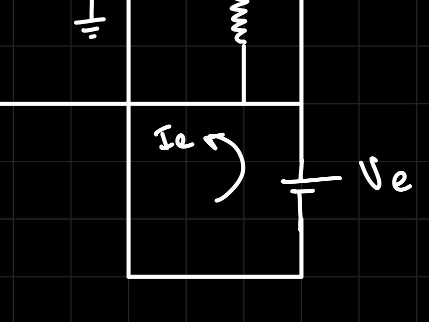
Power gain in dB = $10 \log_{10} |A_p|$

if you combine two phase shifted waves, it is destructive

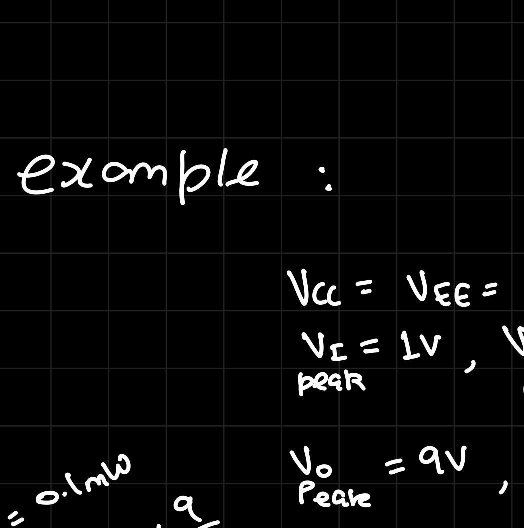
⇒ Amplifier Power Supply

where are the extra signals coming from ?
↳ DC Power Source
↳ decides the gain of the amplifier

Actual amplifiers do not provide ∞ amplification. There is some threshold which is allocated by the DC src (BIAS)



$$P = V_{cc} I_{cc} + V_e I_e$$



$$P_{dc} + P_i = P_L + P_{dissipated}$$

example :

$V_{cc} = V_{EE} = 10V$

$V_{I\,peak} = 1V$, $V_{RMS_I\,peak} = \frac{1}{\sqrt{2}} V$

$V_{o\,peak} = 9V$, $V_{RMS_o\,peak} = \frac{9}{\sqrt{2}} V$

$I_{cc} = I_{EE} = 9.5\,mA$

$R_L = 1k\Omega$

$i_{I\,peak} = 0.1mA$, $i_{RMS_I\,peak} = \frac{0.1}{\sqrt{2}} mA$

$P_i = 0.1mW$
$P_L = \frac{9}{\sqrt{2}} \times \frac{9}{\sqrt{2}}$
↓ $V_o \times I_o = \frac{81}{4}$
$= 40.5mW$

Voltage gain : $A_v = \frac{9/\sqrt{2}}{1/\sqrt{2}} = 9 = 19.1\,dB$

Current gain : $A_i = \frac{V_o/R_L}{0.1} = \frac{9/1000}{0.1 \times 10^{-3}} = 90 = 39.08\,dB$

Power gain : $A_p = A_i \times A_v = 810 = 29.1\,dB$

Power drawn from dc src : $P_{dc} = 190mW$
↳ $V_{cc} I_{cc} + V_{EE} I_{EE}$

Power dissipated in amp: $P_{diss} = P_L - P_i - P_{dc}$
$= 149.5\,mW$

efficiency = $\frac{P_L}{P_{dc}} \times 100 = 23.1\%$

→ Amplifier saturation

Signal clipping : if amp not designed properly
↓ Amp error

IE: Tutorial 1

q1) hole concentration

$p(x) = 10^{16} (1 + x/L)^2 \ cm^{-3}$

$L = 12 \mu m$ $\qquad -L \le x \le 0$

hole diffusion constant $D_p = 10 cm^2/s$

p type → majority : holes

doping with GaAs

hole diffusion current density = ?

$$J_p = -q D_p \frac{dp(x)}{dx}$$

$$= -1.6\times10^{-19} \times 10 \times 2\times10^{16} \times (1+\frac{x}{L}) \times \frac{1}{L}$$

$L = 12\times10^{-6}$

$$= -1.6\times10^{-2} \times 2 \times \left(1 + \frac{x\times10^{6}}{12}\right) \times \frac{10^6}{12}$$

$$= \left(\frac{-3.2\times10^{7}}{12}\right)\left(1+\frac{10^6 \times x}{12}\right)$$

at $x = 0$ → $\frac{-3.2\times10^{7}}{12} = -2.666\times10^{3}$ A/cm^3

unit change: $-26.6 \ A/cm^2$

q2) $A_{v_o} = 100 V/V$ when? (unit Less)

(a) $R_i = 10 R_s$, $R_L = 10 R_o$

$$v_i = \frac{R_i}{R_i + R_s} v_s = \frac{10}{11} v_s$$

$$V_o = \frac{R_L}{R_L + R_o} A_{v_o} v_i = \frac{10}{11} \times A_{v_o} \times \frac{10}{11} V_s$$

$$\frac{V_o}{V_s} = \frac{100}{121} A_{v_o} = 82.64$$

(b) $R_i = R_s$, $R_L = R_o$

$$V_o = \frac{R_L}{R_L + R_o} A_{v_o} \frac{R_i}{R_i + R_s} V_s$$

$$\frac{V_o}{V_s} = \frac{1}{2} A_{v_o} \cdot \frac{1}{2} = \frac{1}{4} A_{v_o} = 25$$

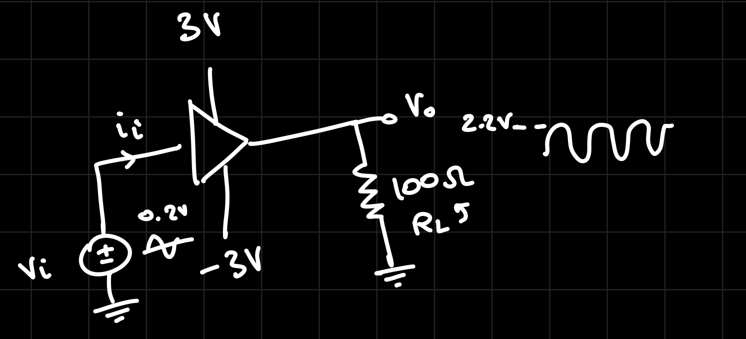
(c) $R_i = \frac{R_s}{10}$, $R_L = \frac{R_o}{10}$

$$V_o = \frac{R_L}{R_L + R_o} A_{v_o} \frac{R_i}{R_i + R_s} V_s$$

$$\frac{V_o}{V_s} = \frac{R_o(1/10)}{R_o(1/10) + R_o} A_{v_o} \times 11 \ V_s$$

$$\frac{V_o}{V_s} = 11 \times 11 A_{v_o} = 121 A_{v_o} = 12100$$

q3)



$$\text{voltage gain} = A_v = \frac{v_o}{v_i} = \frac{2.2}{0.2} = 11 \ V/V$$

$$A_v|_{dB} = 20 \log_{10} |A| = 20.8 dB$$

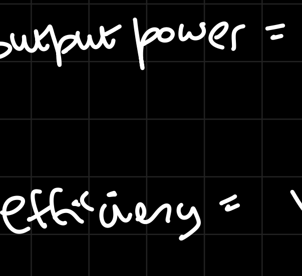
$$\text{power gain} = A_p = \frac{P_o}{P_i} = \frac{(2.2/\sqrt{2})^2/100}{\frac{0.2}{\sqrt{2}} \times \frac{1}{\sqrt{2}} \times 10^{-3}} = 242$$

for power and sinusoidal voltage src, we use the Rms value

$$A_{P_{dB}} = 10 \log_{10} 242 = 23.8 \ dB$$

Power supply: $\underbrace{2\times3}_{V} \times \underbrace{20\times10^{-3}}_{I} = 120 mW$

because

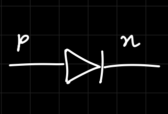


$$\text{output power} = \frac{V_{rms}^2}{R_L}$$

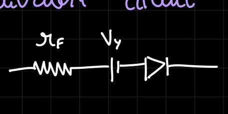
$$\text{efficiency} = \frac{V_{out}}{V_{in}} \times 100$$

* Tut : 2

PN Junction diode



* diode equivalent circuit



Silicon diode : 0.7V
Germanium diode : 0.3V
Gallium Arsenide diode : 1.3V
Ideal diode : 0V

r_f : forward resistance
V_γ : cutoff voltage

$$r_{ac} = r_f = \eta \frac{V_T}{I_L}$$

η : utility factor
$V_T = 25mV$: thermally generated voltage

Bohrsman const $=1.38 \times 10^{-23}$ J/K ; temp (Kelvin) : room temp → 298K

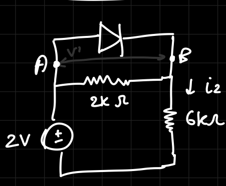
$$V_T = \frac{KT}{q}$$

q → magnitude of charge $= 1.6 \times 10^{-19}C$

$\approx 25mV$ at room temperature

---

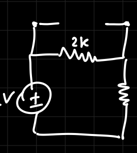
q1) $V_{on} = 0.7V$
diode "on" voltage
current i_2 (mm)



(a) if V' > 0.7V,
diode is on
diode replaced by equivalent cutoff voltage
forward bias

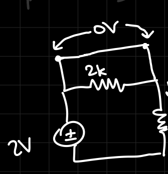
$$V_{AB} = 2 \times \frac{2000}{2000+6000} = 0.5V$$

diode is always off → oc



$$i(t) = \frac{2}{8000} = \underline{0.25mA}$$

(b) for ideal case → diode is always on
because 0.5V > 0V always
replaced by equivalent voltage cutoff

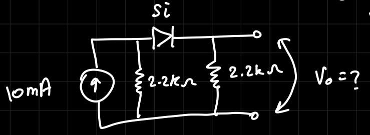


$$i(t) = \frac{2}{6000} = \underline{0.33mA}$$

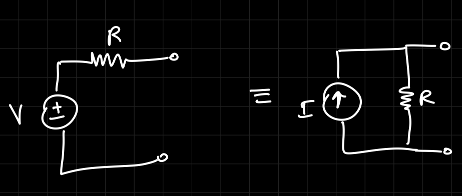
we apper voltage at 2kΩ is 0.5V
and since 0.5 > 0 , diode is always on

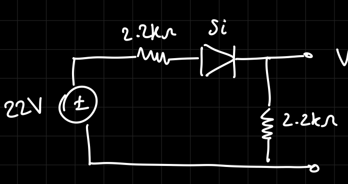
q2) output voltage V_o, diode current I_D ?

note : diode senses only voltage SRC
$V_{Th} = 0.7V$

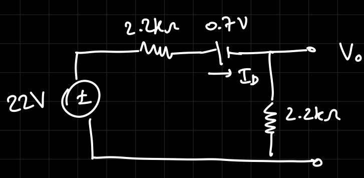


norton → thevenin
SOURCE TRANSFORMATION





diode always on because 22 > 0.7



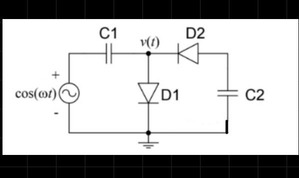
$$-22 + 2.2 I_D + 0.7 + 2.2 I_D = 0$$

$$I_D = \frac{21.3}{4.4} mA = 4.84 mA$$

$$V_o = I_D R = 4.84 \times 2.2$$

$$V_o = 10.648 V$$

q3)



$v(t) = ?$

diodes and cap are ideal in this ckt

q6)

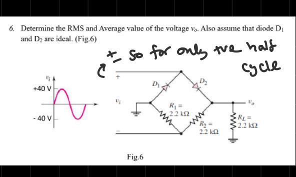
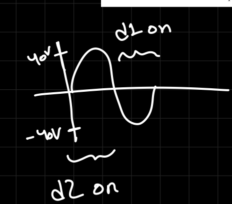

6. Determine the RMS and Average value of the voltage v_o. Also assume that diode D_1 and D_2 are ideal. (Fig.6)

Fig.6



AC input

$$V_{RMS} = \frac{V_o}{\sqrt{2}}$$

$$V_{avg} = \frac{2V_o}{\pi}$$

for ideal diode, the short ckt volt = 0V

$$V_{avg} = \frac{1}{T} \int_{\langle T \rangle} V_m \sin(\omega t)\, d\omega t$$

$$= \frac{V_m}{\pi} \left[-\cos(\omega t)\right]_0^{\pi}$$

$$= \frac{V_m}{\pi} \left[-\cos(\pi) + \cos(0)\right]$$

$$= \frac{2V_m}{\pi}$$

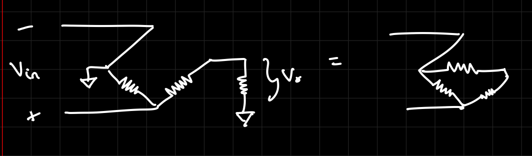
$$V_o = \frac{40 \times 2.2k}{4.4k} = 20V$$

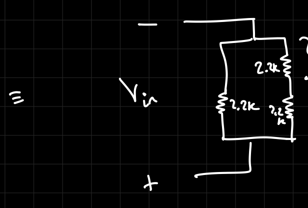
$$V_{RMS} = \frac{20}{\sqrt{2}} V = 10\sqrt{2} V = \underline{14.14 V}$$

$$V_{avg} = \frac{40}{\pi} = \underline{12.7V}$$

don't leave in $\sqrt{2}$ form
solve it

for the negative half cycle (not needed according to ques)



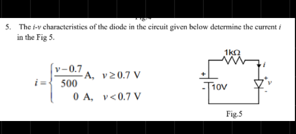


$$V_o = \frac{-40 \times 2.2k}{4.4k} = -20V$$

$$V_{RMS} = \frac{-20}{\sqrt{2}} V = -14.14V$$

$$V_{avg} = \frac{-20 \times 2}{\pi} = \frac{-40}{\pi} = \frac{40}{3.14} \approx -12.7V$$

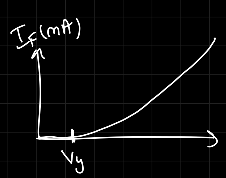
q5)


5. The i-v characteristics of the diode in the circuit given below determine the current i in the Fig 5.

$$i = \begin{cases} \frac{v-0.7}{500} A, & v \geq 0.7 V \\ 0 A, & v < 0.7 V \end{cases}$$

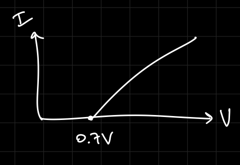
Fig.5

not a silicon diode



general diode → exponential V-I characteristic

but in the ques V-I characteristic is linear
so not a silicon diode



ques diode

which will have greater slope

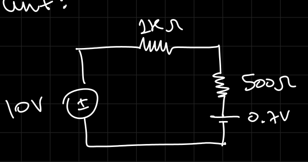
for $V \geq 0.7V$ → $i = \frac{V-0.7}{500}$

$$500i + 0.7 = V$$

$$500\, di + 0 = dV$$

$$\frac{dV}{di} = 500\Omega$$ (Resistance) offered by the PN junction diode

circuit :



$$-10 + 0.7 + 1500\, i = 0$$

$$i = \frac{9.3}{1.5} mA = 6.2mA$$

q4)

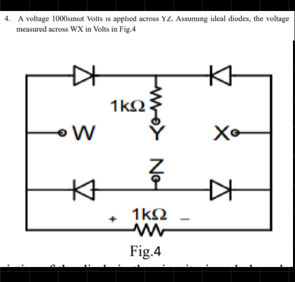
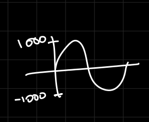

4. A voltage 1000sinωt Volts is applied across YZ. Assuming ideal diodes, the voltage measured across WX in Volts in Fig.4

Fig.4



for +ve half cycle,
all diodes are off
all oc
→ 0V

for -ve half cycle
all are short ckt
→ 0V

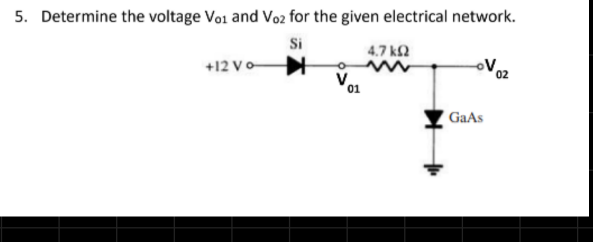
overall = 0V

reality : for Si diode → 4 × 0.7
⇒ 2.8 V

Tutorial 3

q5)

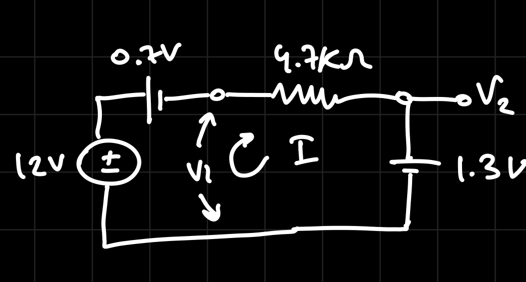
5. Determine the voltage V_{01} and V_{02} for the given electrical network.



also calculate the series current of the circuit

input: DC 12V

Si diode : on
GaAs diode : on



$$-12+0.7+4700I+1.3=0$$

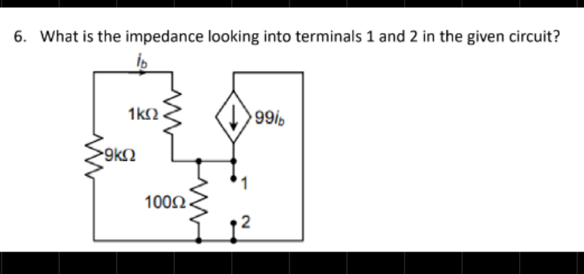
both the diodes are on
it means that both the diodes are replaced by cutoff voltage

$$I = \frac{10}{4.7} mA = 2.12mA$$

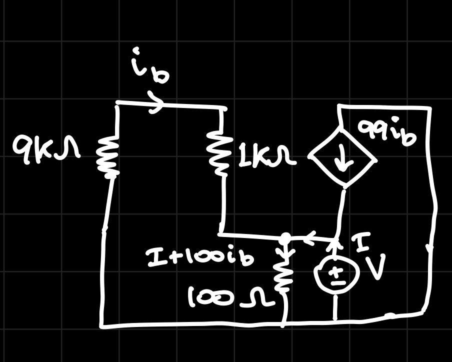
$$V_2 = 1.3V$$
$$-12+0.7+V_0 = 0$$
$$V_1 = 11.3V$$

q6)

6. What is the impedance looking into terminals 1 and 2 in the given circuit?



Thevenin Equivalent
but dependent src
so, add a test voltage source of V



no independent source is present in the network.
So, we apply a test src across terminal 1 and 2
either a current or voltage src

$$10k\, i_b + 100I + 10k\, i_b = 0$$

$$-V + 100I + 10k\, i_b = 0$$

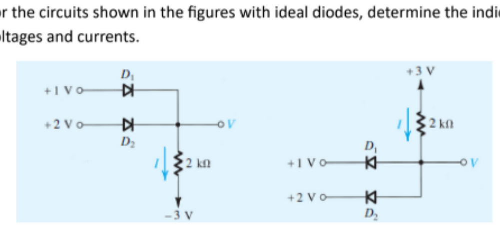
let test src → V volts
I current

$$I = -200 i_b$$
$$\frac{I}{-200} = i_b$$

$$V = 100I + -50I \Rightarrow \frac{V}{I} = Z_{Th} = 50\Omega$$

q7)

7. For the circuits shown in the figures with ideal diodes, determine the indicated voltages and currents.



(a) Which diode will conduct first?
D2

now D1 will not conduct because its n side has 2V and p side has 1V

(b) D1 will conduct first
D2 will not conduct

in reverse bias, the lesser potential one will conduct

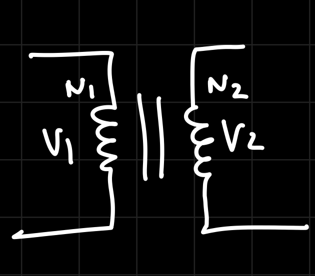
Rectifier: AC → pulsating DC

AC: varies with time : bidirection ±
DC: const with time : unidirection +/−

Rectifier
↳ half wave
↳ Full wave
  ↳ Centre Tap
  ↳ Bridge
    ↳ Better

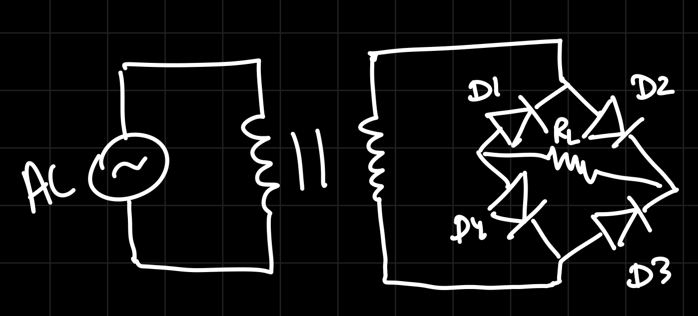
Transformer doesn't work with DC

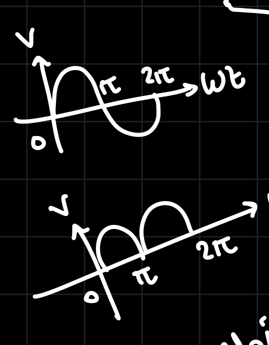
$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$



transformer
↳ step up
↳ step down

generally, used for power transformation





+ve half cycle → D2, D4 on
−ve half cycle → D1, D3 on

pulse repitition time:
originally: 2π
rectified: π

$$V_{avg} = \frac{1}{T}\int_T V_m \sin\omega t\, d\omega t$$
$$= \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t\, d\omega t$$
$$= \frac{V_m}{\pi}\Big[-\cos\omega t\, d\omega t\Big]_0^{\pi}$$
$$= \frac{2V_m}{\pi}$$

$$V_{Rms} = \frac{1}{T}\int_0^T v_o^2(t)\, d\omega t$$
$$= \frac{1}{\pi}\int_0^{\pi} V_m^2 \sin^2(\omega t)\, d\omega t$$
$$= \frac{V_m^2}{2\pi}\int_0^{\pi}(1-\cos(2\omega t))\, d\omega t$$

$$\cos(2A) = 1 - 2\sin^2 A$$
$$\sin^2 A = \frac{1-\cos(2A)}{2}$$

$$= \frac{V_m^2}{2\pi}\Big[\omega t - \frac{\sin(2\omega t)}{2}\Big]_0^{\pi}$$
$$= \frac{V_m^2}{2\pi}(\pi + 0 + 0 + 0)$$
$$= \frac{V_m^2}{2}$$

for half wave rectifier,

V_{avg} / DC value $= \frac{V_m}{\pi}$
and Rms value: $V_{Rms} = \frac{V_m}{2}$

NOTE: for full wave bridge rectifier, two diodes conduct at a time. That's why we always consider two cutoff voltages

And for center tapped rectifier, only one diode conducts at a time

q1)

1. A full-wave bridge-rectifier circuit with a 1k load operates froma120V(rms)60-Hz house hold supply through a 12 to 1 step-down transformer having a single secondary winding. It uses four diodes, each of which can be modelled to have a 0.7 V drop for any current. What is the peak value of the rectified voltage across the load? For what fraction of a cycle does each diode conduct? What is the average voltage across the load? What is the average current through the load?

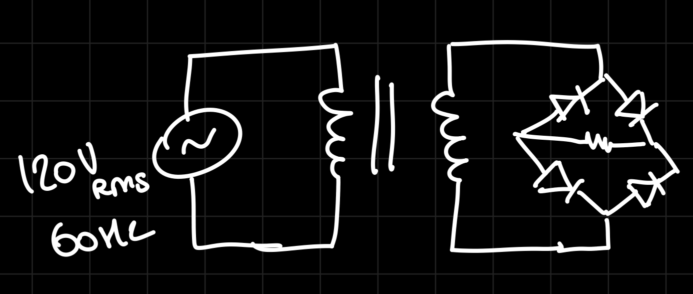
$N_1 = 12$
$N_2 = 1$

$$\frac{V_2}{V_1} = \frac{1}{12} \Rightarrow V_2 = \frac{120}{12} = 10V_{Rms}\ 60Hz$$
$$V_{peak} = 10\sqrt{2} = 14.14V$$

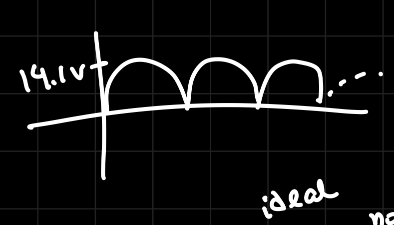
$$R_L = 1000\Omega$$

The given bridge rectifier is Si based

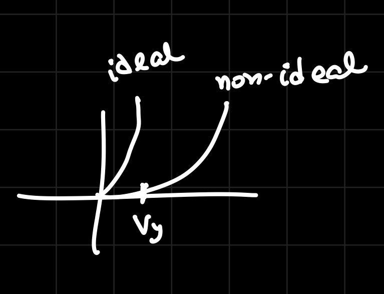
$$V_\gamma = 0.7V$$

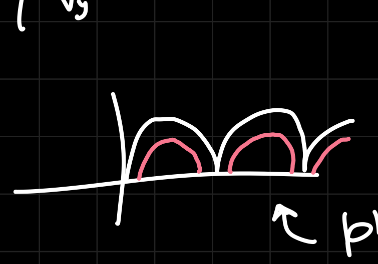


$$V_2 = \frac{N_2}{N_1} \times V_1 = \frac{1}{12} \times 120V_{Rms} = 10V_{Rms}$$
$$= 14.14V$$



→ This result is for ideal analysis





• : non ideal
• : ideal
↑ phase angle diff?

So, the actual peak voltage is

$$V_o = 10\sqrt{2} - 2V_\gamma = 14.14 - 1.4 = 12.74V$$

$V_{gamma} = V_{threshold}$ of diode

This would have been correct if it was on ideal diode case

$$V_{avg} = \frac{2V_o}{\pi} = \frac{2\times 12.74}{3.14} = 8.11V$$

$$V_{Rms} = \frac{V_o}{\sqrt{2}} = \frac{12.74}{\sqrt{2}} \simeq 9V$$

$\omega t \to \phi$

$$V_{avg}\big|_{non\text{-}ideal} = \frac{1}{\pi}\int_{\theta}^{\pi-\theta}(V_m \sin\phi - 2V_\gamma)\, d\phi$$

$$\theta = \sin^{-1}\Big[\frac{2V_\gamma}{V_m\sqrt{2}}\Big] = \sin^{-1}\Big[\frac{1.4}{10\sqrt{2}}\Big]$$

$$\theta = 0.991 \text{ rad}$$

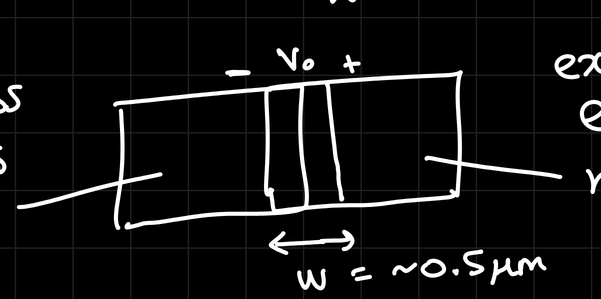
$$V_{avg} = \frac{1}{\pi}\int_{\theta}^{\pi-\theta}(V_m \sin\phi - V_\gamma)\, d\phi$$

$$r_{ac} = r_f = \eta \frac{V_T}{I_L}$$

ZENER DIODE

depletion width: $W = \sqrt{\frac{2\epsilon}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_o - V)}$

$$E = \frac{|V_R|}{W}$$



excess holes
p

excess e^-
n

trivalent impurity

pentavalent impurity

acceptor ion N_A

donor ion N_D

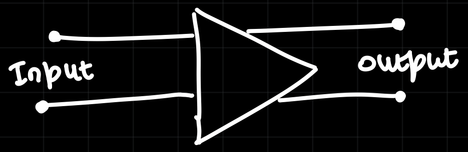
$$V_o = \frac{KT}{q}\ln\frac{N_A N_D}{n_i^2}$$

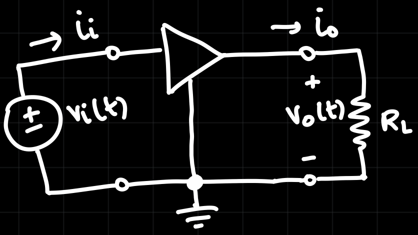
n_i : intrinsic ion
n_A : acceptor ion
n_D : donor ion

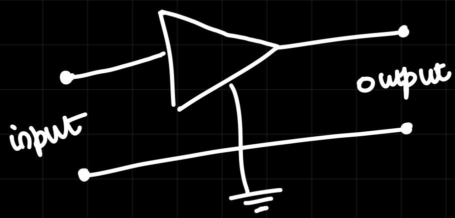
highly doped PN junction diode
reverse biased

<u>Revision:</u> Integrated Electronics

AMPLIFIER:
- ↳ voltage : massive volt gain
- ↳ Power : minimal volt gain, massive current gain







voltage gain: $A_v = \dfrac{v_o}{v_i}$

current gain: $A_i = \dfrac{i_o}{i_i}$

Power Gain : $A_p = \dfrac{v_o i_o}{v_i i_i} = A_v A_i$

GAIN in dB

Voltage Gain $= 20 \log_{10} |A_v|$ dB

Current Gain $= 20 \log_{10} |A_i|$ dB

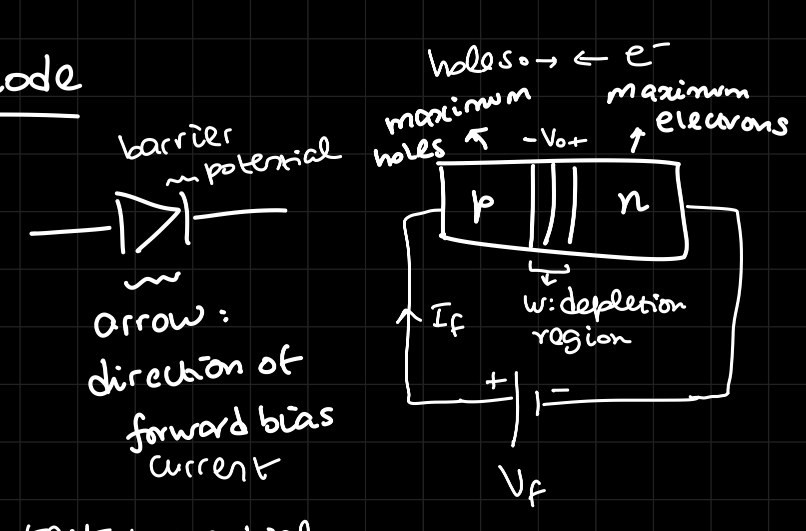
Power Gain $= 10 \log_{10} |A_p|$ dB

Amplifier Power

signals are amplified through DC power supplied to the amplifier

→ TF taking the lecture

Zener Diode



V_0 : contact potential

$$V_0 = \frac{KT}{q} \ln\left[\frac{N_A N_D}{n_i^2}\right] \text{ Volt}$$

$V_T = \frac{KT}{q}$ at room temp, $T = 298K$
$K = 1.38 \times 10^{-23}$ J/K
$q = 1.6 \times 10^{-19}$ C

$$V_T = \frac{T}{11{,}600} \text{ Volt} \simeq 25mV$$

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

W ↓ width of depletion region

ε = electric permittivity
$\varepsilon = \varepsilon_0 \varepsilon_r$
ε_0 ↓ 8.854×10^{-12} F/m

V = applied voltage
V_0 = contact potential

in reverse bias → applied voltage = -ve = V
$V_0 - V$ = +ve
w = +ve ↑
Width of depletion region increases in reverse bias

In forward bias, depletion layer decreases
In reverse bias, depletion layer increases
wrt no bias

Diode general current equation

$$I = I_s\left[e^{\frac{V}{\eta V_T}} - 1\right]$$

$\eta = 1$ for Ge and 2 for Si
2.7 for GaAs

I_s = leakage current

V_f = forward bias voltage

$$\frac{V_F}{V_T} \rightarrow \frac{V_F}{\sim 25 \times 10^{-3}} = \frac{V_F}{25} \times 10^3 > 1 \checkmark \text{ for forward bias}$$

$e^{V_F/V_T} >>> 1$
neglect the -1 wrt e^{V_F/V_T} in above eqn

$$\boxed{I_F \simeq I_s\left(e^{V_F/V_T}\right)}$$

for reverse bias,

$$V = -ve = -V_R$$

$$e^{-V_R/V_T} <<< 1$$

$$\boxed{I_R \simeq -I_0}$$

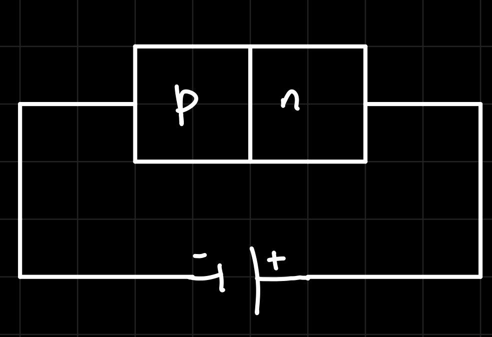
Si → 14 → 2,8,4
Ge → 32 → 2,8,18,4
valence e^- easier to leave for Ge but we still use Si why?

$I_{S_{Si}}$ = nA $I_{S_{Ge}}$ = μA

because leakage current is way higher in case of germanium

ZENER DIODE

① Always works under reverse bias
② In forward bias, it acts as normal pn junction diode
③ Zener diode works always under high electric field



$$E = \frac{|V_R|}{W}$$

③ As we increase the reverse voltage, depletion layer also increases

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

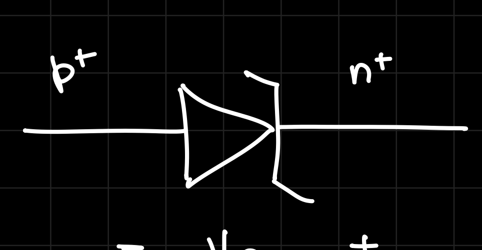
$$W \propto \frac{1}{\sqrt{\text{doping concentration}}}$$

and since $E \propto \frac{1}{W}$

works in very high electric field
≡ very high current

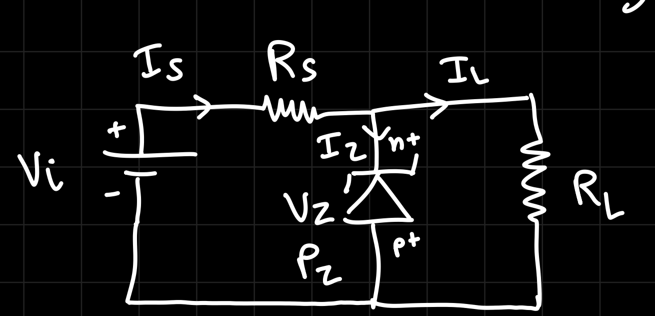
④ Zener diode is a very highly doped pn junction

1 impurity in every 10^3 atom (Si/Ge)
normal pn junction diode → $1:10^6$



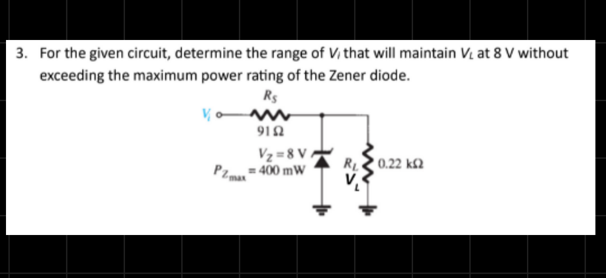
p^+, n^+ : highly doped

Application: as a ...
voltage regulator
shunt regulator



$$I_S = I_Z + I_L$$

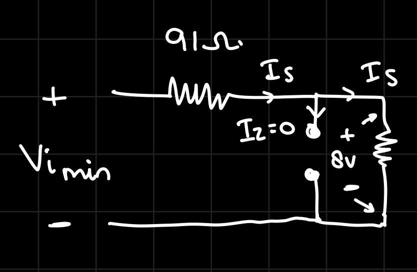
Q3)


3. For the given circuit, determine the range of V_i that will maintain V_L at 8 V without exceeding the maximum power rating of the Zener diode.

Range = $V_{i_{min}} - V_{i_{max}}$

in case of $V_{i_{min}}$, Zener diode acts as open circuit

in case of $V_{i_{maximum}}$, Zener diode replaced by its equivalent cutoff voltage V_Z

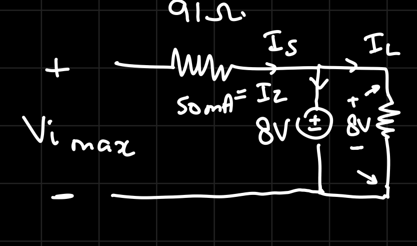


$P_Z = 400$ mW
$V_Z = 8V$
$P_Z = V_Z I_Z$
$I_Z = 50mA$ when zener diode works properly

$$\frac{V_{i_{min}} \times 220}{220 + 91} = 8$$

$V_{i_{min}} = 11.3V$

$V_{i_{max}}$ →



$$-8 + I_L(220) = 0$$
$$I_L = 36.36mA$$

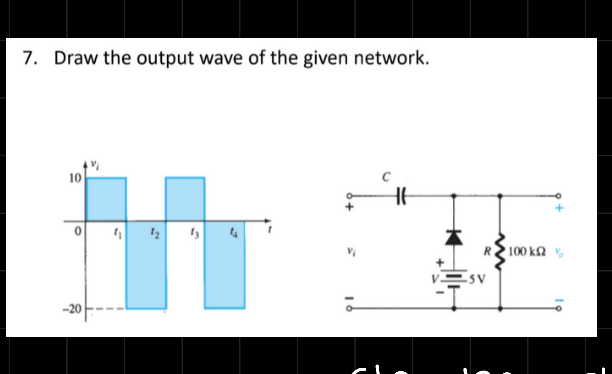
$$I_S = I_Z + I_L = 50 + 36.36 = 86.36mA$$

$$8 - V_{i_{max}} + 91(86.36 \times 10^{-3}) = 0$$
$$V_{i_{max}} = 15.858V$$

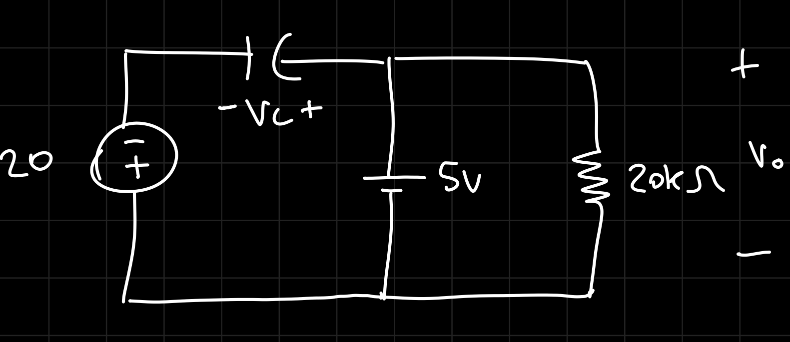
Range: $11.3V < V_i < 15.85V$

AC analysis of PN Junction diode

Q)

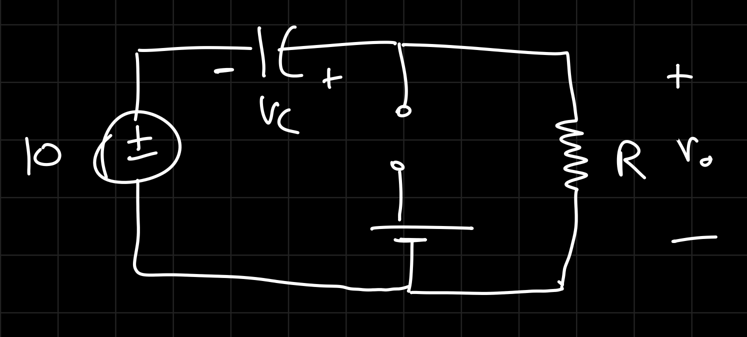

7. Draw the output wave of the given network.

Clamper ckt



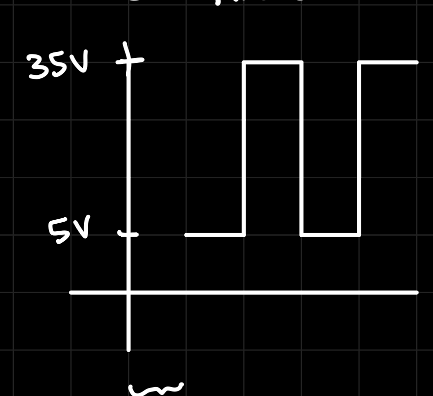
$$20 - V_C + 5 = 0$$
$$V_C = 25V$$
$$V_o = 5V$$

NOTE: capacitor doesn't allow sudden change of voltage



$$-10 - V_C + V_o = 0$$
$$V_o = 10 + V_C = 10 + 25 = 35V$$

NOTE: we take case where diode is on first

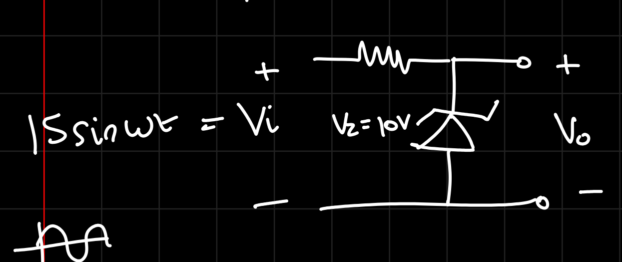


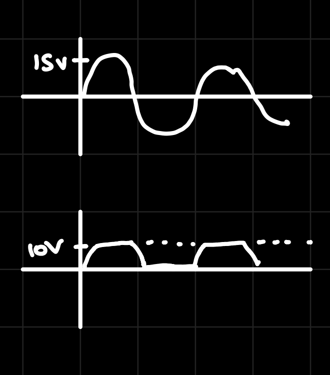
delay because ckt starts from -ve cycle

negative clamper because diode was n p

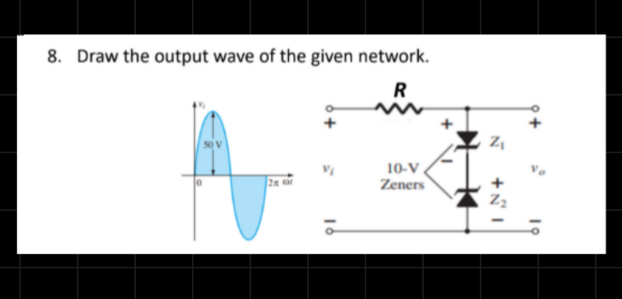
positive clamper shifts waveform downwards

Clipper

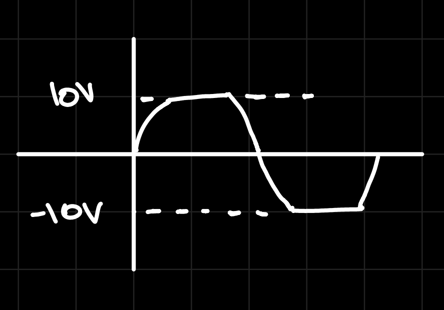




Q)


8. Draw the output wave of the given network.

+ve half cycle → 0 - 10V
Z_2 → off



zener diode → used for voltage/current regulation

BJT

case : 1 → ACTIVE [amplifier]

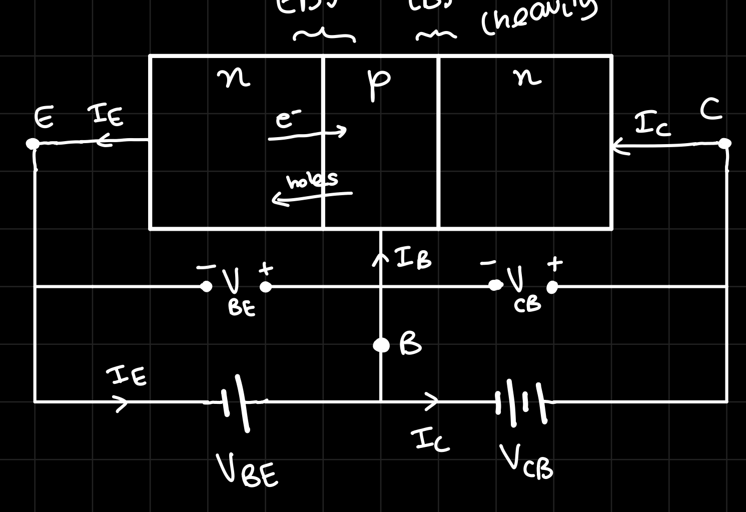
V_{BE} = 0.7V Forward bias
V_{CB} = 0V Reverse bias

case : 2 → saturation [switch]

V_{BE} = 0.8V Forward bias
V_{CB} = 0.7V Forward bias

NPN TRANSISTOR

EBJ → emitter base junction (forward biased)
CBJ → collector base junction (heavily reverse biased)



$I_E = I_B + I_C$

e^- from E → B much more desirable than holes from B → E^-

E : highly doped with n type semiconductor
→ so less # of holes
B : lightly doped with p type semiconductor

→ for forward bias EBJ, the concentration

$$n_p(0) \propto e^{\frac{V_{BE}}{V_T}}$$

→ e^- concentration : $n_p(0)$ is highest at the E side and lowest (~ zero) at the C side

$$n_p(0) = n_{po} e^{\frac{V_{BE}}{V_T}}$$

note : V_T ⇒ thermal voltage
V_T = 25mV at room temperature

V_{BE} : forward BE voltage

Electron diffusion current

$$I_n = A_E q D_n \frac{dn_p(x)}{dx}$$

D_n → e^- diffusivity in the base
q → e^- charge
A_E → Cross sectional area of the BEJ

$$I_n = A_E q D_n \left(-\frac{n_p(0)}{W}\right) \quad \to \text{C/second}$$

− → current flows opposite to the flow of e^-
W → width of the base region

* base region is lightly doped as compared to the emmitor region
→ so concentration of holes as compared to e^- from E is less
→ I_B is very less (~negligible)
→ So, $I_C \simeq I_E$

What if we remove the base region ? Since E is highly doped, there will be some diffusion current flowing but can it function properly ?

$$I_C = I_S e^{V_{BE}/V_T}$$

$$I_S = \frac{A_E q D_n n_{po}}{W} = \frac{A_E q D_n n_i^2}{W N_A}$$

$$n_{po} = \frac{n_i^2}{N_A}$$

n_i = intrinsic carrier density
N_A = doping concentration of base

[SOCKETS
bind listen accept
htons
↳ used to convert port "number" to the format used by the internet

β = common emmitor current gain
↳ influenced by
→ W
→ relative doping of base emitter regions (N_A/N_D)

High value of β ⇒
thin base (W ~ nm)
lightly doped base
heavily doped emmiter
(small N_A/N_D)

$$\beta = \frac{I_C}{I_B} \qquad \text{and} \qquad i_E = i_C + i_B$$

$$i_B = \frac{I_C}{\beta}$$

$$\beta i_E = \beta i_C + i_C$$

$$i_E = \left(\frac{\beta+1}{\beta}\right) i_C$$

let $\alpha = \frac{\beta}{\beta+1}$

$$i_E = \frac{i_C}{\alpha}$$

common base → $\alpha = \frac{i_C}{i_E}$

let $\beta = 0.99$
$\alpha \simeq 1$
$i_C = i_E$

eg) $I_B = 10\mu A$
$I_C = 600\mu A$

$\alpha, \beta = ?$

$\beta = 60$

$\alpha = \frac{60}{61} = 0.9836$

eg) $V_{BE} = 0.76V$ npn
$I_C = 10mA$

$I_C = ?$ at $V_{BE} = 0.7V$

$$I_C = I_S e^{V_{BE}/V_T}$$

$$10^{-2} = I_S e^{30.4}$$

$$I_S = \frac{10^{-2}}{e^{30.4}}$$

$$I_C = \frac{10^{-2}}{e^{30.4}} e^{0.7/0.025} = 10^{-2} \cdot e^{28-30.4}$$

$$= 10^{-2} \cdot e^{-2.4}$$
$$= 9 \times 10^{-4} A$$
$$= 0.9mA$$

$$10 \times 10^{-4} = e^{-30.4} e^{V_{BE}/0.025}$$

$$\log_e 10^{-3} = -30.4 + \frac{V_{BE}}{0.025}$$

$$V_{BE} = (-6.9 + 30.4)\, 0.025$$

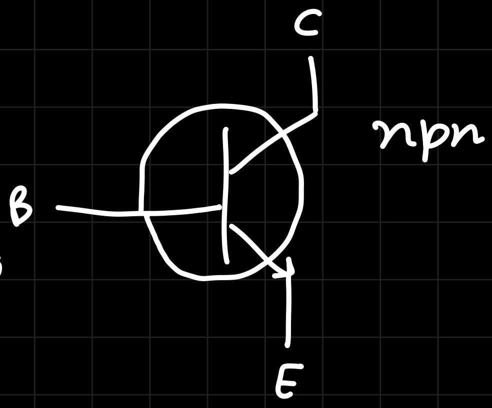
$$V_{BE} = 0.5875 V$$

formula used → $I_C = I_S e^{\frac{V_{BE}}{V_T}}$

SOMETHING

BJT (Revision)

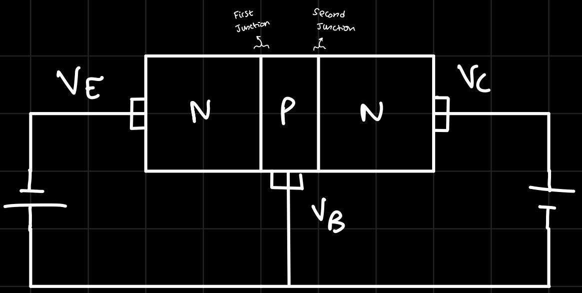
controlling current on one terminal by varying voltage on two terminals



Application:

Amplifier → only in active mode
Switch → saturation and cutoff mode

for NPN BJT →



not exactly but can be related with

≃ 

Active mode:	FB	and	RB	$V_E < V_B$, $V_B < V_C$
Cutoff mode:	RB	and	RB	$V_E > V_B$, $V_B < V_C$
Saturation mode:	FB	and	FB	$V_E < V_B$, $V_B > V_C$

$$I_C = I_S e^{V_{BE}/V_T}$$

$$\beta = \frac{I_C}{I_B}, \quad \alpha = \frac{I_C}{I_E}$$

$$I_{SE} = \frac{I_S}{\alpha}$$ ≡ saturation current of the emmiter region

Lecture (~Tutorial)

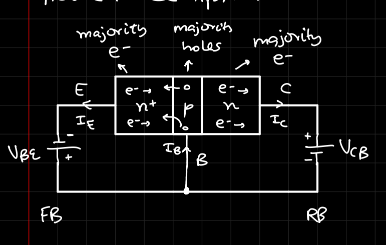
BJT → why bipolar?

because current is flowing through majority and minority charge carriers.

In BJT, we have 2 junctions
↳ Emmiter-base Junction
↳ Collector-base Junction

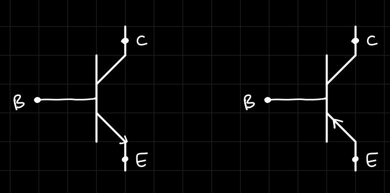
EBJ	CBJ	Mode	Application
FB	RB	Active	Amplifier
RB	RB	Cutoff	off-switch
FB	FB	Saturation	On-switch
RB	FB	Inverted	Not used generally (amp but with very low gain)

Active mode npn →

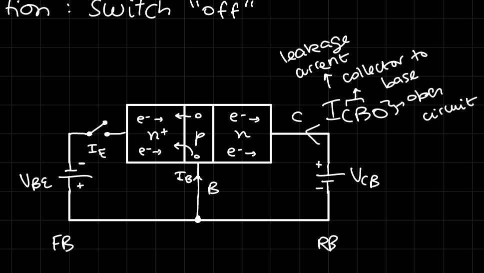


$I_E = I_B + I_C$

Area(C) ~ 50%
Area(B) ~ 10%
Area(E) ~ 40%
} general idea (not actually precise)



condition : switch "off"



This is common base configuration

#Generally ⤵
$\alpha = \frac{I_C}{I_E}$

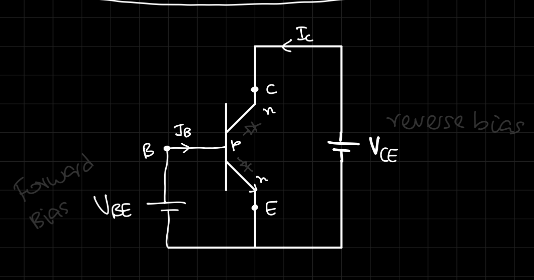
$I_C = \alpha I_E + I_{CBO}$
majority ↳ minority

$I_E = I_B + I_C$

$I_C = \alpha I_B + \alpha I_C + I_{CBO}$
$(\alpha - 1) I_C = \alpha I_B + I_{CBO}$
$I_C = \frac{\alpha}{1-\alpha}(I_B) + \frac{I_{CBO}}{1-\alpha}$ → let $\beta = \frac{\alpha}{\alpha - 1}$

$I_C = \beta I_B + \frac{I_{CBO}}{1 - \frac{\beta}{1+\beta}}$

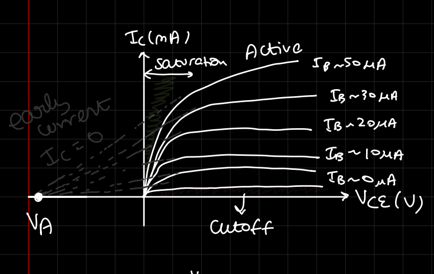
$\boxed{I_C = \beta I_B + (1+\beta) I_{CBO}}$



for active mode →
EBJ : FB
CBJ : RB

Depletion layer decreases in CBJ
Base width modulation ↙

VBE fixed
VCE ↑ ✓
depletion layer ↑
Collector region overlap
overall base width ↓
I_C ↑
} Early effect



$i_C = I_S e^{V_{BE}/V_T}$ # $V_T = 25mV$ for room temp

$i_{C_{new}} = I_S e^{V_{BE}/V_T}\left[1 + \frac{V_{CE}}{|V_A|}\right]$

$10V < |V_A| < 100V$

$\frac{\partial i_{C_{new}}}{\partial V_{CE}} = I_S e^{V_{BE}/V_T}\left[0 + \frac{1}{|V_A|}\right]$

$\frac{\partial V_{CE}}{\partial i_{C_{new}}} = \frac{|V_A|}{I_S e^{V_{BE}/V_T}} = \boxed{\frac{|V_A|}{i_C} = \boxed{r_o}}$

early effect impedance

$I_C = \beta I_B$

NUMERICAL

Q1) for a given transistor, check whether the transistor works in active or cutoff mode?

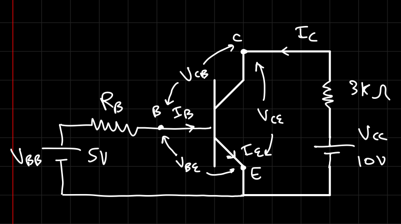
Assume that transistor is Si based

→

	EBJ	CBJ
Active :	FB	RB
Cutoff :	RB	RB

assume $\beta = 100$

(i) 200kΩ
(ii) 50kΩ



$-V_{BB} + I_B R_B + V_{BE} = 0$

$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5 - 0.7}{200}$ mA

$I_B = 0.0215mA$

V_{BE} → replaced by cutoff voltage
here $V_{BE} = 0.7V$

and $V_{CE_{saturation}} = 0.2V$ to $0.3V$

$I_C = \beta I_B = 2.15mA$

in 2nd loop:

$-3k I_C + 10 - V_{CE} = 0$

$V_{CE} = 10 - 3\times10^3 \times 2.15\times10^{-3}$
$= 3.55V >>> V_{BE}$
(Active mode)

(ii) $R_B = 50k\Omega$

$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5 - 0.7}{50} \times$ mA

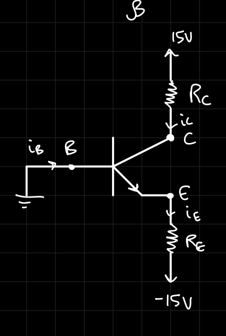
$= 0.086 mA$

$I_C = \beta I_B = 8.6mA$

$V_{CE} = V_{CC} - I_C R_B$
$V_{CE} = 10 - 8.6 \times 3$
$= -15.8V <<< V_{BE}$ (0.7V)
↓
saturation mode

Q2) The transistor shown has $\beta = 100$ and exhibits a V_{BE} of 0.7V and $i_C = 2mA$. Design the ckt so that current of 2mA flows through the collector and a voltage of +5V appear at the collector.

→ $i_B = \frac{i_C}{\beta} = 20\mu A$



$i_C = \frac{15 - V_C}{R_C}$

$R_C = \frac{15 - V_C}{i_C}$

$V_C = 5V$ given

$R_C = \frac{15-5}{2}$ kΩ
$= 5 k\Omega$

$V_{BE} = 0.7V = V_B - V_E$
$V_B - V_E = 0.7V$
$V_E = -0.7V$

$i_E = \frac{V_E - (-15)}{R_E}$

$\beta = 100$
$\alpha = \frac{\beta}{1+\beta} = \frac{100}{101} = 0.99$

$\alpha = \frac{i_C}{i_E} \Rightarrow i_E = \frac{i_C}{\alpha} = \frac{2}{0.99}$ mA

$= 2.02mA$

$R_E = \frac{V_E + 15}{i_E}$

$= \frac{-0.7 + 15}{2.02}$ kΩ $= 7.079 k\Omega$

$i_{C1} = I_S e^{V_{BE_1}/V_T}$

$i_{C2} = I_S e^{V_{BE_2}/V_T}$

$\frac{i_{C1}}{i_{C2}} = e^{\frac{V_{BE_1} - V_{BE_2}}{V_T}}$

$\log_e(0.5) = \frac{V_{BE_1} - V_{BE_2}}{V_T}$

$\ln(\frac{1}{2}) = \frac{V_{BE_1} - 0.7}{V_T}$

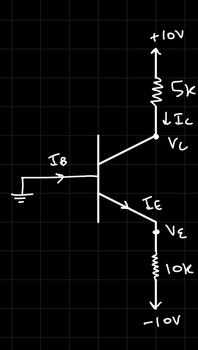
$V_{BE_2} = -0.7 - \ln(0.5)V_T$

$= -0.7 - (-0.693 \times 25\times10^{-3})$

$= 0.717V$ ✗

0.683V

Q) $V_E = -0.7V$
$\beta = 50$
$i_E, i_B, i_C, V_C = ?$



$I_E = \frac{V_E - (-10)}{10}$ mA

$= \frac{10 - 0.7}{10}$ mA

$= 0.93mA$

$\alpha = \frac{I_C}{I_E} \Rightarrow I_C = I_E\left(\frac{\beta}{\beta+1}\right) = 0.93 \times \left(\frac{50}{51}\right)$ mA

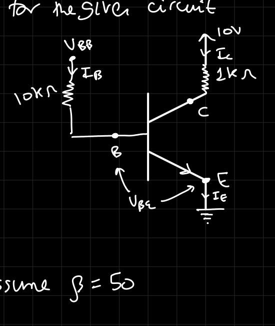
$= 0.91mA$

$V_C = 10 - 5k I_C$

$V_C = 10 - 5 \times 0.91 = 5.45V$

$I_B = 0.0182mA$

Q) for the given circuit



$V_{BB} = 1.7V$
active mode?

While keeping V_{BB} const find that value to which R_C should be increased in order to obtain →
(a) operation at edge of saturation
(b) operation at deep saturation with $\beta_{forced} = 10$

Hint →
(a) for edge of saturation, consider $V_{CE} = 0.3V$
(b) for deep sat, V_{CE} is considered 0.2V

assume $\beta = 50$

$I_B = \frac{V_{BB} - V_{BE}}{R_B}$

$= \frac{1.7 - 0.7}{10}$ mA

$= 0.1mA$

$V_{BE} = 0.7V = V_B - V_E$
$V_E = 0$

$V_B = 0.7V$

$I_C = \beta I_B = 50 \times 0.1mA$
$= 5mA$

$V_{CC} = I_C R_C + V_{CE} \Rightarrow 5 \times 1 + V_{CE} = 10$
$V_{CE} = 5V >>> V_{BE}$
(active)

2nd)
1.94kΩ
9.8kΩ

$\alpha = \frac{I_C}{I_B}$ common emmiter

$\beta = \frac{I_C}{I_E}$ common base

$\gamma = \frac{I_E}{I_B}$ common collector

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

Q1)

1. In the amplifier circuit shown in figure 1, the values of R_1 and R_2 are such that the transistor is operating at V_{CE} = 3 V and I_C = 1.5 mA when β is 150. For a transistor with β of 200, find the operating point (V_{CE}, I_C). (Assume R_1&R_2 are fixed)

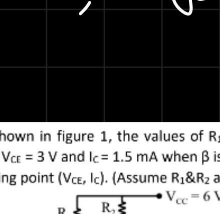


figure 1

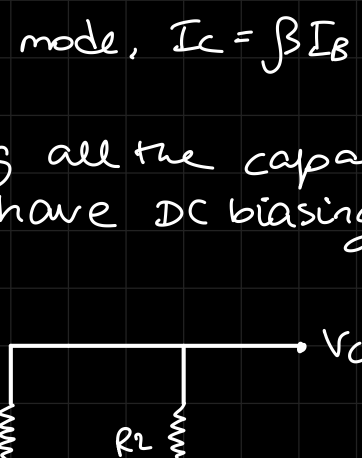
given: amplifier
so, active mode
$V_{BE} > 0$: FB
$V_{CB} < 0$: RB

given: $V_{CE} = 3V$ $I_C = 1.5mA$

for active mode, $I_C = \beta I_B + (\beta+1) I_{CBO}$

removing all the capacitors because we have DC biasing

$V_{BE} = 0.7V$ for Si



$V_{BE} = V_B - V_E$
$V_B = V_{BE} + V_E$

$V_{CC} + I_B R_1 + 0.7 + I_E \overset{\to 0}{} = 0$ $I_C = \beta I_B$
$6 + 10^5 R_1 + 0.7 = 0$
$R_1 = -6.7 \times 10^5 \Omega$ X
$I_B = \frac{1.5}{150} mA = 0.01mA$

$6 + I_C R_2 + V_{CE} + I_E = 0$
$6 + 1.5 mA \cdot R_2 + 3 + 0 = 0$
$R_2 \cdot 1.5 \times 10^{-3} = -9$ X

$\frac{6 - V_B}{R_1} = I_B \Rightarrow R_1 = (6 - 0.7 - V_E)10^5$

KVL: ① $-6 + I_C R_2 + 3 = 0$
$1.5m \cdot R_2 = 3$
$R_2 = 2k\Omega$

② $-6 + I_B R_1 + V_{BE} = 0$
$-6 + 0.01m \cdot R_1 + 0.7 = 0$
$R_1 = 530k\Omega$

② $\beta = 200$

$I_C = 1.5mA$
$I_C = \beta I_B + (\beta+1) I_{CBO}$
let this be negligible because not given

X $\left\{ \begin{array}{l} I_C = \beta I_B \\ I_B = \frac{1.5}{2} A \times 10^{-5} \\ I_B = 7.5 \mu A \end{array} \right.$

I_C not known

$-6 + R_1 I_B + V_{BE} = 0$
$530k \cdot I_B = 5.3$
$I_B = \frac{5.3}{530} mA = 0.01mA$

$I_C = \beta(0.01m) = 2mA$

$-6 + I_C \cdot R_2 + V_{CE} = 0$
$V_{CE} = 6 - 2 \cdot 2 = 2V$

Q3)

3. Determine the voltages at all nodes and the currents through all branches in given figure3. Assume β = 100.

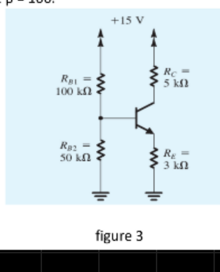
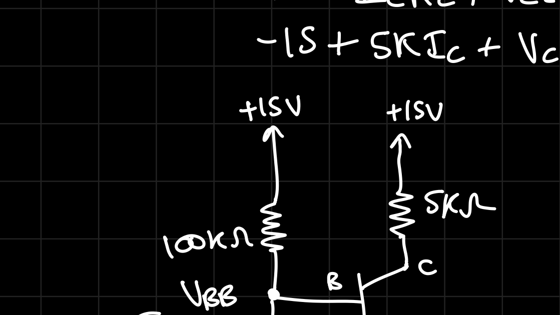


figure 3

$\beta = 100$

$-15 + I_C R_C + V_{CE} + I_E R_E = 0$
$-15 + 5k I_C + V_{CE} + I_E \cdot 3k = 0$



$-15 + 5k(I_C) + V_{CE} + 3k I_E$

$V_{BB} = \frac{50k}{150k} \cdot 15 = 5V$

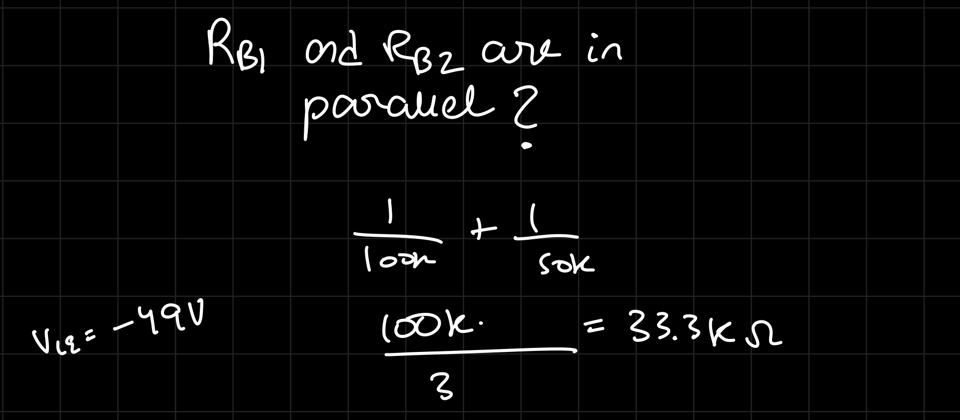
$I_B \neq 0$ practically

R_{B1} and R_{B2} are in parallel ?

$\frac{1}{100k} + \frac{1}{50k}$

$\frac{100k}{3} = 33.3k\Omega$

$V_{CE} = -49V$



$-5 + 33.3k I_B + 0.7 + I_E 3k = 0$
$-15 + 5k \cdot I_C + V_{CE} + I_E 3k = 0$
$I_C = \beta I_B = 100 I_B$

$-15 + 5k \cdot 100 I_B + V_{CE} + I_E 3k = 0$

$10 + (33300 - 5100) I_B + 0.7 - V_{CE} = 0$

$\Rightarrow I_B = \frac{V_{CE} - 10.7}{282} mA$

$I_B = \frac{5 - 0.7}{33.3} mA = 0.128mA$

$I_C = 12.8mA$

$V_{CE} = 282(0.13) + 10.7 = 47.36V$

$-15 + 5k \cdot I_C + V_{CE} + 3k \cdot I_E = 0$

$-5 + 33.3k I_B + 0.7 + I_E 3k = 0$
$-5 + 33.3(0.128) + 0.7 + I_E \cdot 3k = 0$
$4.3 - 4.2624 = I_E \cdot 3k$
$I_E = 112.8A$ X

$\alpha = \frac{I_C}{I_E}$ $\alpha = \frac{\beta}{\beta+1} = \frac{100}{101} = 0.99$

$I_E = \frac{12.8}{0.99} mA = 12.92mA$

Q)

2. For a silicon based BJT shown in figure 2, find R_B to establish V_{CE} = 2V, Assume V_{BE} = 0.7 V.

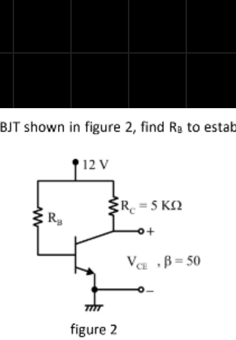
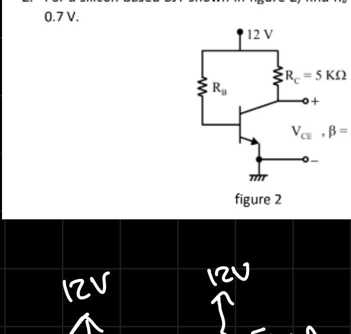


figure 2



$V_{BE} = 0.7V$

$\beta = 50$

$-12 + I_B R_B + V_{BE} = 0$

$I_C = \beta I_B$

$I_B R_B = 11.3V$

$-12 + I_C(5k) + V_{CE} = 0$

$I_C = \frac{10}{5} mA = 2mA$

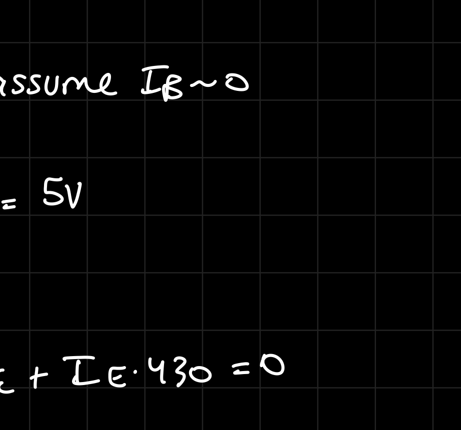
$I_B = \frac{2mA}{50} = 0.04 mA$

$R_B = \frac{11.3}{0.04} k\Omega = \frac{1130}{4} k\Omega$
$= 282.5k\Omega$

Q4) active Region

$\beta >>>$ $V_{BE} = 0.7V$

$I_C = ?$



① $\left\{ \begin{array}{l} -15 + R_C I_C + V_{CE} \\ + I_E \cdot 430 = 0 \end{array} \right.$

since $\beta >>>$
and $\beta = \frac{I_C}{I_B}$ so, assume $I_B \sim 0$

$V_{BB} = \frac{5k}{15k} \times 15 = 5V$

$-15 + I_B \cdot 10k + V_{BE} + I_E \cdot 430 = 0$

$\underbrace{I_B \cdot 10k}_{\sim 0} + I_E \cdot 430 = 14.3$

$I_E = \frac{14.3}{430} = 0.03A$
$= 3mA$

for finding $R_{Th} \to$

we remove all the independent srces
so the two resistances are in parallel

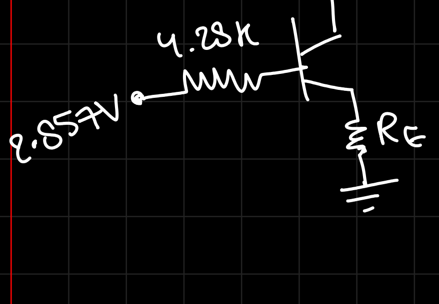
Q5)

5. In the transistor circuit as shown in figure 5 below, find the value of resistance R_E in KΩ. Assume β is large.

figure 5

$\Rightarrow$ $I_E \sim I_C$
$I_B \sim 0$
$\beta >>$

$\frac{15 + 6}{15k \cdot 6} \Rightarrow \frac{15k \cdot 2}{7} \Rightarrow \frac{30k}{7} =$
$4.28k\Omega$



$I_B = \frac{2.857 - 0.7}{4.28} mA$

$I_B = 0.5mA$

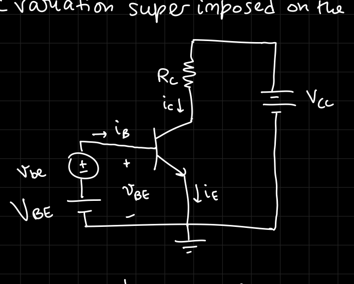
Simulation on Thursday 13/02/25
Quiz on Friday 14/02/25 in Tut slot
Practice questions on next Friday (21/02/25)
Midsem on 22/02/25
↳ one A4 cheatsheet allowed

npn

EBJ	CBJ	Mode	Application
FB	RB	Active	Amplifier
RB	RB	Cutoff	off-switch
FB	FB	Saturation	On-switch
RB	FB	Inverted	Not used generally (amp but with very low gain)

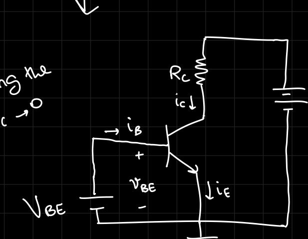
BJT small signal model

AC variation superimposed on the DC



↓ DC analysis

by setting the AC src → 0



$I_C = I_S e^{V_{BE}/V_T}$ $I_B = \frac{I_C}{\beta}$

$V_{CB} > 0.4V$ to keep in active region

$v_{BE} = V_{BE} + v_{be}$

$i_c = I_S e^{v_{BE}/V_T} = I_S e^{V_{BE}/V_T} e^{v_{be}/V_T}$

$i_c = \underbrace{I_c}_{DC} e^{v_{be}/V_T}$

if $v_{be} \ll V_T$ (i.e. peak of $v_{be} \ll 10mV$)
then,

$i_c \approx I_c\left(1 + \frac{v_{be}}{V_T}\right)$

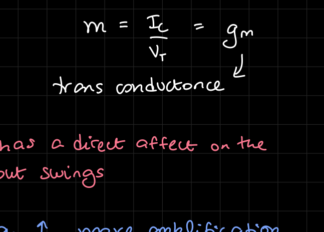
↓

$i_c = I_c + \frac{I_c}{V_T} v_{be}$

AC part of i_c $= \frac{I_c}{V_T} v_{be}$

$= \underbrace{g_m v_{be}}_{\text{trans conductance}}$; $g_m = \frac{I_c}{V_T}$

$i_c = I_c + \frac{I_c}{V_T} v_{be}$



① $v_{be} = 0$
$v_{BE} = V_{BE}$
$i_c = I_c = I_S e^{V_{BE}/V_T}$

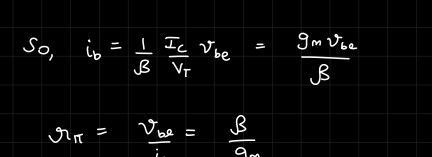
② $v_{be} \neq 0$
$v_{BE} = V_{BE} + v_{be}$

Slope of • → $\frac{I_c + \frac{I_c}{V_T} v_{be} - I_c + \frac{I_c}{V_T} v_{be}}{V_{BE} + v_{be} - V_{BE} + v_{be}}$

$m = \frac{I_c}{V_T} = \underbrace{g_m}_{\text{trans conductance}}$

g_m has a direct affect on the output swings

if $g_m \uparrow$, more amplification, more power consumption, higher V_{BE} required.



$g_m = \left.\frac{\partial i_c}{\partial v_{BE}}\right|_{i_c = I_c}$

* To determine resistance seen by v_{BE}, we calculate the total base current i_B using:

$i_B = \frac{i_c}{\beta} = \frac{I_c}{\beta} + \frac{1}{\beta}\frac{I_c}{V_T} v_{be}$

$i_B = I_B + i_b$

So, $i_b = \frac{1}{\beta}\frac{I_c}{V_T} v_{be} = \frac{g_m v_{be}}{\beta}$

$r_\pi = \frac{v_{be}}{i_b} = \frac{\beta}{g_m}$

$\boxed{r_\pi = \frac{\beta}{g_m}}$

$r_\pi = \frac{\beta}{g_m} = \frac{\beta V_T}{I_c} = \frac{V_T}{I_B}$

* Emmiter current i_E

$\alpha = \frac{i_c}{i_E}$ → $i_E = \frac{i_c}{\alpha}$

$r_E = \frac{v_{be}}{i_E}$

$r_E = \frac{v_{be} \cdot \alpha}{i_c} = \frac{\alpha}{g_m} = \frac{V_T}{I_E}$

$i_e = \frac{i_c}{\alpha} = \frac{1}{\alpha}\frac{I_c}{V_T} v_{be} = \frac{I_E}{V_T} v_{be}$

generally, $r_\pi \gg r_e$

$v_{be} = i_b r_\pi = i_e r_e$

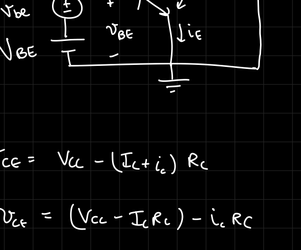
$r_\pi = \left(\frac{i_e}{i_b}\right) r_e$

$\frac{i_e}{i_c} = \alpha = \frac{\beta+1}{\beta}$

$\frac{i_e}{i_b} = \beta + 1$

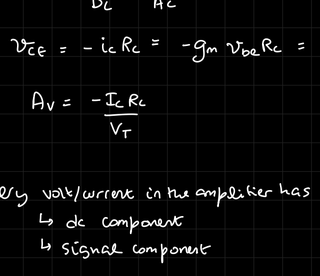
$r_\pi = (\beta+1) r_e$

π-model



Voltage gain:

$v_{CE} = V_{CC} - i_C R_C$



$v_{CE} = V_{CC} - (I_c + i_c) R_c$

$v_{CE} = (V_{CC} - I_c R_c) - i_c R_C$

$v_{CE} = \underbrace{V_{CE}}_{DC} - \underbrace{i_c R_c}_{AC}$

$v_{ce} = -i_c R_c = -g_m v_{be} R_c = (-g_m R_c) v_{be}$

$A_v = -\frac{R_c}{r_e}$

[illegible]

MODELS

π-MODEL

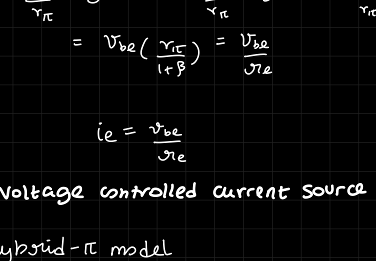
$i_e = \frac{v_{be}}{r_e}$

Voltage controlled current source

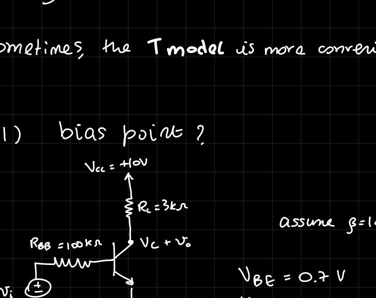
hybrid-π model
[illegible]

Sometimes the T model is more convenient.

eg 1) bias point?



DC analysis



$-V_{BB} + I_B \cdot 100k + V_{BE} = 0$

$-10 + V_{CE} + I_c \cdot 3k = 0$
$V_{CE} + I_c \cdot 3k = 10$

$I_B = \frac{3 - 0.7}{100}$ mA

$I_c = \beta I_B = 2.3mA$

V_{BE} = biasing point

$g_m = \frac{I_c}{V_T} = \frac{2.3m}{25m} = 92mA/V$

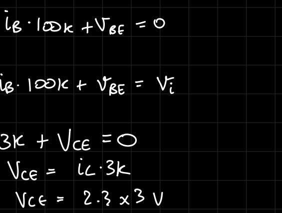
$r_\pi = \frac{\beta}{g_m} = 1.09k\Omega$

$V_C = V_{CC} - I_C R_C = 10 - 2.3 \times 3$

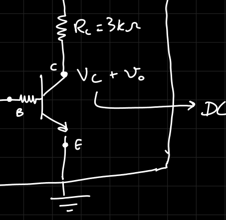
$V_C = 3.1V$

pi-model

DC sources in AC model



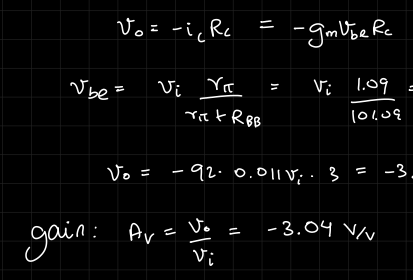
AC equivalent ckt



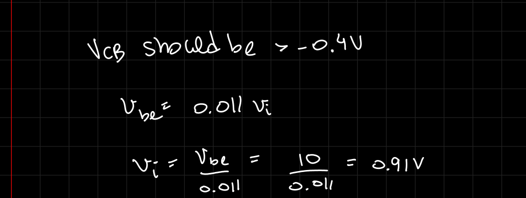
$-v_i + i_B \cdot 100k + v_{BE} = 0$

$i_B \cdot 100k + v_{BE} = v_i$

$i_c \cdot 3k + V_{CE} = 0$
$V_{CE} = i_c \cdot 3k$
$V_{CE} = 2.3 \times 3$ V



π model



$v_o = -i_c R_c = -g_m v_{be} R_c$

$v_{be} = v_i \frac{r_\pi}{r_\pi + R_{BB}} = v_i \frac{1.09}{101.09} = 0.011 v_i$

$v_o = -92 \cdot 0.011 v_i \cdot 3 = -3.04 v_i$

gain: $A_v = \frac{v_o}{v_i} = -3.04$ V/V

V_{CB} should be $> -0.4V$

$v_{be} = 0.011 v_i$

$v_i = \frac{v_{be}}{0.011} = \frac{10}{0.011} = 0.91V$

$v_{CE} = V_{CE} + |v_o|$

$= 3.1 \pm 2.77 = (5.83, 0.33)$

* to satisfy small signal approximation, $v_{be} < 10mV$ peak

$v_{BE} = 0.71 \pm 0.01 = (0.72, 0.7)$

$V_{CB} = -0.38V$ # forward Bias

for saturation, $V_{CB} < -0.4$
but $V_{CB} > -0.4$
So, amp is in active mode

Bipolar Junction Transistor

Active Region → Amplifier
EBJ : FW Bias
CBJ : RV Bias

$V_C > V_B > V_E$

Cutoff Region → Switch
EBJ : RV
CBJ : RV

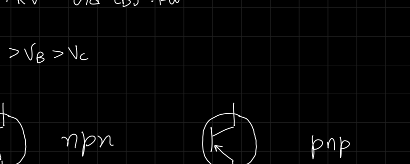
$V_E > V_B$ and $V_C > V_B$

Saturation Region → Switch
EBJ : FW
CBJ : FW

$V_B > V_E$ and $V_B > V_C$

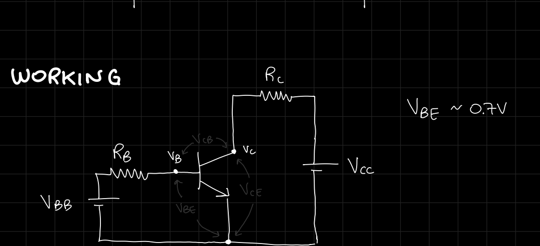
Inverted Region → useless (gain very low)
EBJ : RV and CBJ : FW

$V_E > V_B > V_C$



npn   pnp

WORKING



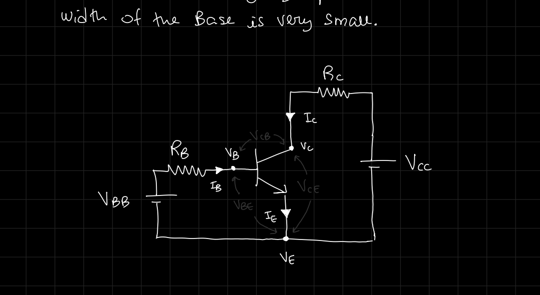
$V_{BE} = 0.7V$

We know that emitter region is heavily doped and since it is n-type, the majority carriers are e^-.

When we power the circuit, the e^- from the -ve terminal of V_{BB} will repel the e^- at emitter and they will move towards the base which is lightly doped so that less combination of holes.

Now, in the base, the e^- have 2 routes they can take: either towards the +ve terminal of the V_{BE} or towards the collector region.

Majority of the e^- flow from the emitter will go on the collector and some of them will recombine with the holes in base and go towards the +ve terminal of V_{BE} because B is lightly doped and the width of the Base is very small.



$I_E = I_B + I_C$

Since very less e^- flow out from the Base, $I_E \approx I_C$

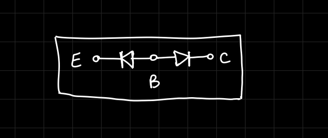
$I_C = \alpha I_E$

$\frac{I_C}{\alpha} = I_B + I_C \Rightarrow I_B = I_C\left(\frac{1-\alpha}{\alpha}\right)$

$I_C = \left(\frac{\alpha}{1-\alpha}\right) I_B$

let $\beta = \frac{\alpha}{1-\alpha}$ $\frac{1}{\beta} = \frac{1}{\alpha} - 1 \Rightarrow \alpha = \frac{\beta}{\beta+1}$

$I_C = \beta I_B$



active mode : $V_{BE} > 0$, $V_{CB} > 0$ FW, RV
cutoff mode : $V_{BE} > 0$, $V_{CB} < 0$ FW, FW
saturation mode : $V_{BE} < 0$, $V_{CB} > 0$ RV, RV

eg) $I_B = 10\mu A$ $I_C = 600\mu A$

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

$\beta = \frac{600}{10} = 60$

$\alpha = \frac{\beta}{\beta+1} = \frac{60}{61} = 0.9836$

eg) $V_{BE} = 0.76V$ $I_C = 10mA$

$I_C = I_S e^{V_{BE}/V_T}$

at room temperature, $V_T = 25mV$

$10 \times 10^{-3} = I_S e^{760/25}$

$\log_e 10^{-2} = \frac{760}{25} + \log_e I_S$

$\log_e I_S = 4.6 - \frac{76 \times 4}{10}$

$= 4.6 - 30.4 = -25.8$

$I_S = e^{-25.8}$ X

$I_S = \frac{1}{159.42 \times 10^{13}} = 0.627 \times 10^{-15} A$

$= 6.27 \times 10^{-16} A$

$I_C = ?$ at $V_{BE} = 0.7V$

$I_C = I_S e^{V_{BE}/V_T}$

$I_C = 6.27 \times 10^{-16} e^{700/25}$

$I_C = 6.27 \times 10^{-16} \times 1.44 \times 10^{12} = 0.9mA$

$V_{BE} = ?$ at $I_C = 10\mu A$

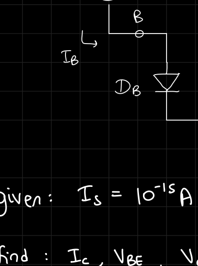
$10 \times 10^{-6} = 6.27 \times 10^{-16} \times e^{V_{BE}/V_T}$

$V_{BE} = 25 \times 10^{-3} \times \ln\left(\frac{10^{11}}{6.27}\right)$

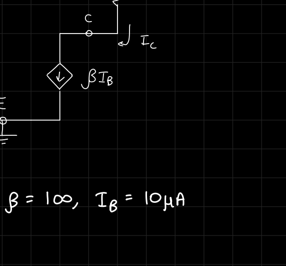
$V_{BE} = 25 \times 10^{-3} \times 23.5$

$V_{BE} = 0.587V$

$I_C = I_S e^{V_{BE}/V_T}$ $\beta = \frac{I_C}{I_B}$ $\alpha = \frac{I_C}{I_E}$

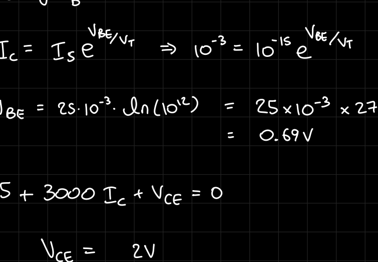


T Model



π - Model

eg)



given : $I_S = 10^{-15} A$, $\beta = 100$, $I_B = 10\mu A$

find : I_C, V_{BE}, V_{CE}

$I_C = \beta I_B = 1mA$

$I_C = I_S e^{V_{BE}/V_T} \Rightarrow 10^{-3} = 10^{-15} e^{V_{BE}/V_T}$

$\Rightarrow V_{BE} = 25 \cdot 10^{-3} \cdot \ln(10^{12}) = 25 \times 10^{-3} \times 27.63$
$= 0.69V$

$-5 + 3000 I_C + V_{CE} = 0$

$V_{CE} = 2V$

for active mode (npn) → $V_{CB} \geq 0$

$V_{CB} \geq 0$ &
CBJ : Reverse

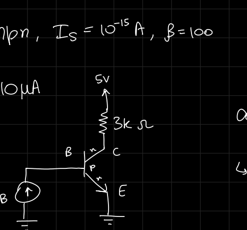
base current in the saturation region $\Rightarrow i_B = \underbrace{\frac{I_S}{\beta} e^{V_{BE}/V_T}}_{EBJ} + \underbrace{I_{SC} e^{V_{BE}/V_T}}_{CBJ}$

$\beta_{forced} = \left.\frac{i_C}{i_B}\right|_{saturation} \leq \beta$

$V_{CE_{saturation}} = V_{BE} - V_{BC}$

pnp →

Active mode : $V_{EB} > 0$ and $V_{CB} < 0$

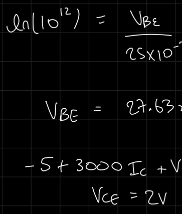


$\beta = \frac{I_C}{I_B}$ → common emitter current gain

$\alpha = \frac{I_C}{I_E}$ → common base curent gain

eg 6.1) npn, $I_S = 10^{-15} A$, $\beta = 100$

$I_B = 10\mu A$



assumption (s):
active mode
↳ EBJ : FW
CBJ : RV

$V_{BE} > 0$ and $V_{CB} < 0$

$I_C = \beta I_B = 1mA$

$I_C = I_S e^{V_{BE}/V_T}$

$10^{-3} = 10^{-15} e^{V_{BE}/V_T}$

$\ln(10^{12}) = \frac{V_{BE}}{25 \times 10^{-3}}$

$V_{BE} = 27.63 \times 25 \times 10^{-3} = \underset{FW}{0.69V}$

$-5 + 3000 I_C + V_{CE} = 0$
$V_{CE} = 2V$

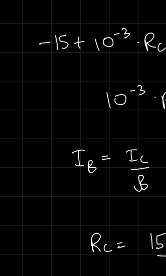
$\left.\begin{array}{l} V_{CE} = V_C - V_E \\ V_{BE} = V_B - V_E \end{array}\right\} V_{CB} = V_{CE} - V_{BE} = \underset{RV}{-1.31V}$

$R_B = \frac{5}{I_B} = \frac{5}{10} \times 10^{6} = 500k\Omega$ X

$\frac{5 - 0.69}{I_B} = 431k\Omega$ ✓

eg2) $\beta = 100$ $V_{BE} = 0.7V$ $i_C = 1mA$

design ckt so that $i_C = 2mA$ and $V_C = 5V$



$-15 + 10^{-3} \cdot R_C + V_{CE} + I_E R_E - 15 = 0$

$\alpha = \frac{\beta}{\beta+1} = \frac{100}{101} = 0.99$

$\frac{I_C}{I_E} = \alpha \rightarrow I_E = \frac{10^{-3}}{0.99} = 1.01mA$

$10^{-3} \cdot R_C + V_{CE} + I_E R_E = 30$

$-15 - 1.01 \cdot 10^{-3} \cdot R_E - V_{BE} = 0$
$R_E = \frac{15.7 k\Omega}{1.01} = 15.5k\Omega$

$-15 + 10^{-3} \cdot R_C + V_{CB} = 0$

$10^{-3} \cdot R_C = 15 - V_{CB}$

$I_B = \frac{I_C}{\beta} = \frac{10^{-3}}{100} = 10^{-5} A$

$R_C = \frac{15-5}{10^{-3}} = 5k\Omega$

* Tutorial 4

Q1)

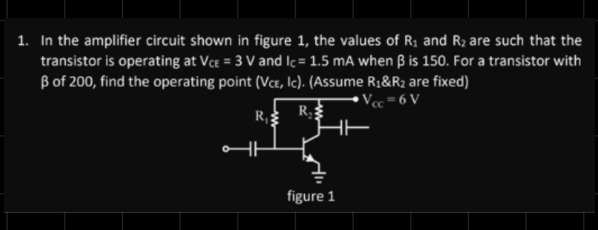
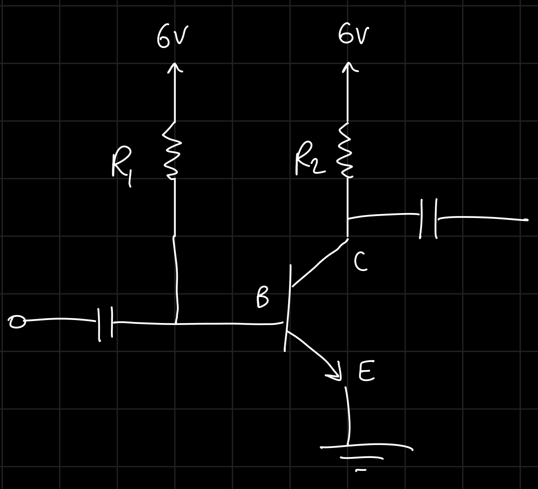
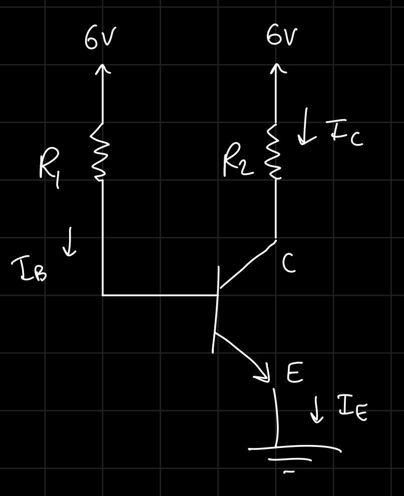

1. In the amplifier circuit shown in figure 1, the values of R_1 and R_2 are such that the transistor is operating at V_{CE} = 3 V and I_C = 1.5 mA when β is 150. For a transistor with β of 200, find the operating point (V_{CE}, I_C). (Assume R_1&R_2 are fixed)

figure 1



Since there is no AC source, we open circuit all the capacitors

NOTE: No AC →
Capacitor ≡ OC
Inductor ≡ SC
VAC = 0



KVL:
$$-6 + \underbrace{I_C}_{1.5mA\ (given)} R_2 + \underbrace{V_{CE}}_{3V\ (given)} = 0$$

$$R_2 = \frac{6-3}{1.5} \text{ k}\Omega = 2\text{k}\Omega$$

$$-6 + R_1 I_B + V_{BE} = 0$$

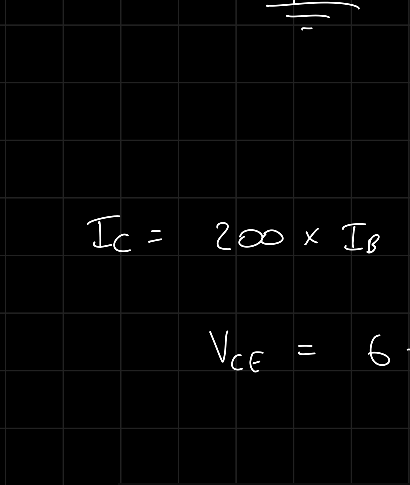
$$\beta = 150, \quad I_B = \frac{I_C}{\beta} = \frac{1.5}{150} mA = 10\mu A$$

$$R_1 = \frac{6-0.7}{10} \times 10^6 \ \Omega$$

$$R_1 = 530 \text{ k}\Omega$$

So $R_1 = 530\text{k}\Omega$ and $R_2 = 2\text{k}\Omega$

(b) for $\beta = 200$, find $\underbrace{V_{CE} \text{ and } I_C}$ operating point



$$-6 + I_C \cdot 2k + V_{CE} = 0$$
$$-6 + 530k \cdot I_B + V_{BE} = 0$$
$$I_B = \frac{6-0.7}{530} mA = \frac{5.3}{530} mA = 10\mu A$$

$$I_C = 200 \times I_B = \underline{2mA}$$

$$V_{CE} = 6 - 2 \cdot 2 = \underline{2V}$$

Q2)

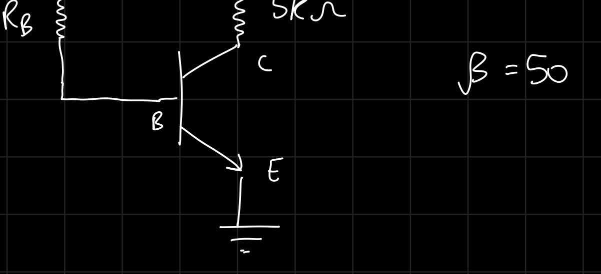
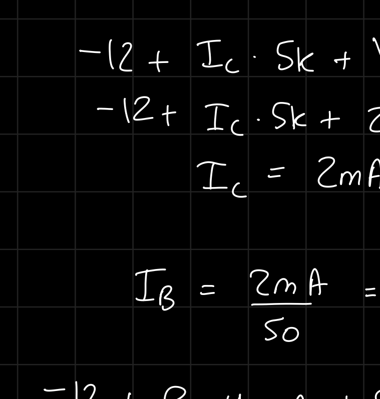

2. For a silicon based BJT shown in figure 2, find R_B to establish V_{CE} = 2V, Assume V_{BE} = 0.7 V.

figure 2



$\beta = 50$

$$-12 + I_C \cdot 5k + V_{CE} = 0$$
$$-12 + I_C \cdot 5k + 2 = 0$$
$$I_C = 2mA$$

$$I_B = \frac{2mA}{50} = 40\mu A$$

$$-12 + R_B \cdot 40\mu A + 0.7 = 0$$

$$R_B = \frac{11.3}{40} M\Omega = 282.5k\Omega$$

Q3)

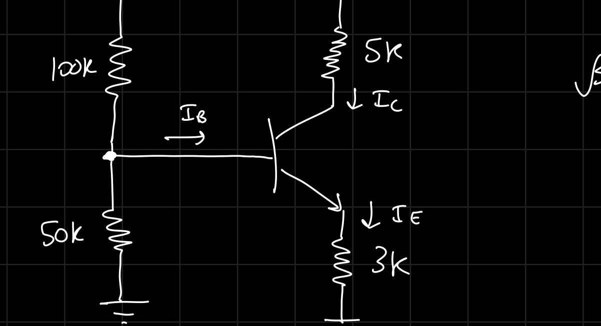
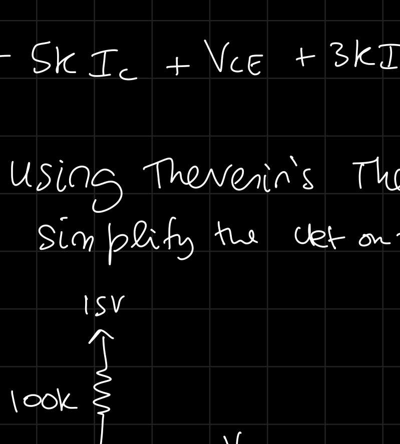

3. Determine the voltages at all nodes and the currents through all branches in given figure3. Assume β = 100.

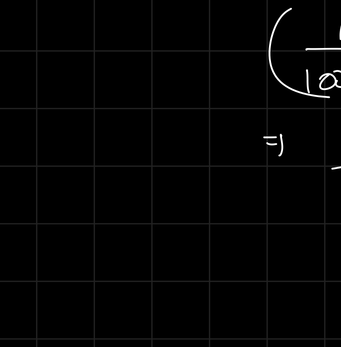
figure 3



$\beta = 100$

$$-15 + 5k I_C + V_{CE} + 3k I_E = 0$$

Using Thevenin's Theorem, we can simplify the ckt on the left



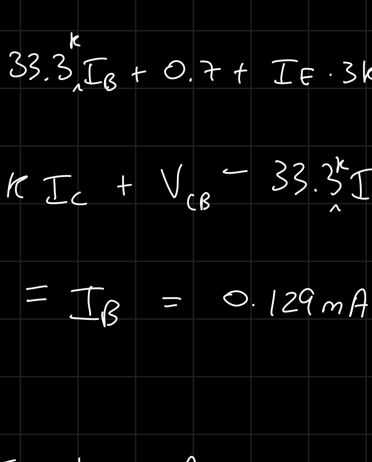
$$V_{Th} = \frac{50k}{150k} \cdot 15 = \frac{15}{3} = 5V$$

$R_{Th} \rightarrow$ SC all V sources

So, $R_{Th} = 100k \parallel 50k$

$$\left(\frac{1}{100k} + \frac{1}{50k}\right)^{-1}$$

$$\Rightarrow \frac{5 \cdot 10^{9}}{150k} = \frac{500 \cdot 10^3}{15} = \frac{100}{3} = 33.3k\Omega$$



$$-5 + 33.3k I_B + 0.7 + I_E \cdot 3k = 0$$

$$-15 + 5k I_C + V_{CB} - 33.3k I_B + 5 = 0$$

$$\frac{5-0.7}{33.3} = I_B = 0.129mA$$

$$I_C = 12.9mA$$

$$\alpha = \frac{\beta}{\beta+1} = \frac{100}{101} = 0.99$$

$$I_E = \frac{I_C}{\alpha} = 13.03mA$$