lect 1 :-

Today's lecture:-

- Introduction
- Semiconductor physics Basics
  - * General Concepts
  - * Doping

* اذا . جودت ابوله سوف اقوم بتدريس مادة Electronic خلال هذا الفصل
* كما نعرف انه Electronic devices تحكم بمعظم اجهزة المحمول في حياتنا اليومية
* لذا فاننا في هذه المحاضرة سوف نتحدث عن Introduction في حين سوف نتحدث عن مفهوم Semiconductor وسوف نتعلم بعد المبادئ العامة عن اشباه الموصلات ثم سوف نتطرق لمفهوم اسمه نوعه Doping.

لذا قبل البدء دعونا نتذكر معاً دائماً في مادة دوائر كهربية I وما سوف يتم تعريفه في هذا المحاضرة.

Introduction

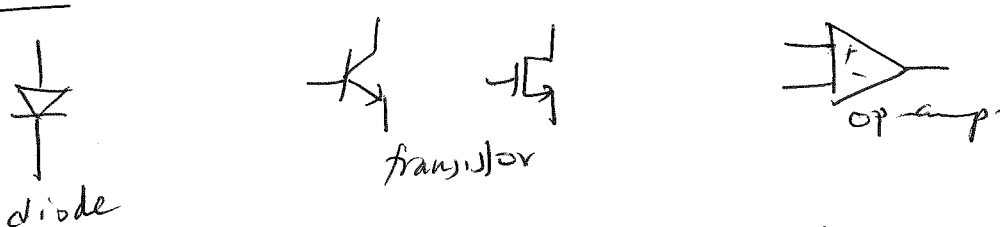
Basic electric Components

ثم دراسة

لذا في استخدام هذه العناصر التي لا طرفية two terminal ليس لها تطبيقات في حياتنا العملية.

وكذلك في عالم الالكترونيات الرقمية مختلف

Electronic devices



باستخدام هذه العناصر يمكن تصميم تطبيقات عديدة

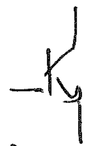
* وكذلك نظراً لان هذه العناصر تعتمد على Semiconductor لذا يجب علينا دراسة Semiconductor باشباه الموصلات وهذا سوف نتعلم بعض الاساسيات التي تحتاجها لفهم العناصر الالكترونية كيف تعمل بالداخل.

②

وان المعلومات هنا لن تكون معرفة كثيرة كما سيتم تغطيته في المساقات التي ستأخذ في
الفيزياء المعنية ب Semiconductor devices ولكننا كأساس لفهم السير على العناصر الإلكترونية

ومبناء على ذلك دعونا نتطرق عن المواضيع التي سوف يتم تغطيتها خلال هذا المساق

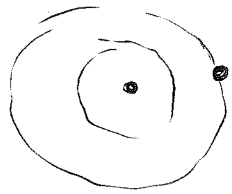
Outline:

- Semiconductor physics
  - Diode
    - Diode circuit
  - Transistor
    - 
      - Bipolar Transistor
      - Bipolar circuit
    - 
      MOS transistor
      MOS circuits

هذه المواضيع سوف يتم تغطيتها من خلال 45 محاضرة

* General Concepts

Orbital تتكون المادة من نواة ويدور الالكترونات حولها في مسارات تسمى



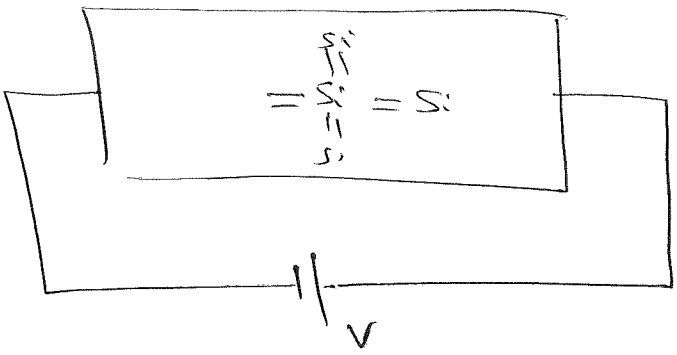
- Differents atoms have differents atoms

Ex:
Sodium : 1 electron
Neon : 8 electrons
Silicon : 4 electrons

let build crystal of Silicon

```
        Si          Si        Si
        ||          ||        ||
Si  =   Si    =     Si   =    Si  =  Si      ⟸ crystal of Silicon
        ||          ||
        Si          Si        Si
```

(3)



- In pure crystal, there is no electron free
- If the temp increase, ⇒ so an electron may be become free

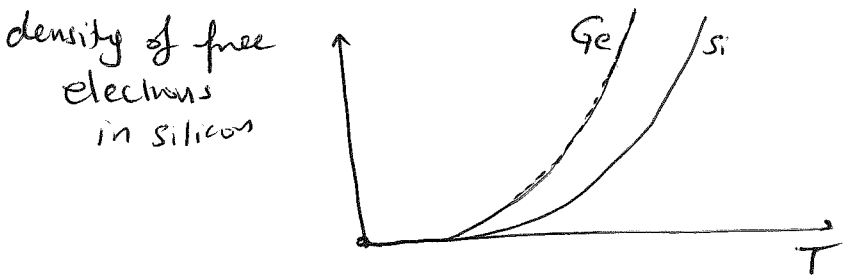
* دالة وهنا كتب عن بعض الأسئلة

Questions:

1) Where do charge carriers come from?
2) What types of charge carriers do we have?
3) How can we modify the density of charge carriers?
4) How do charge carriers move?

هنا بعض الـ Concepts التي تفيد للإجابة عن الأسئلة

Concept of Bandgap Energy



density of electron

$$n_i = 5.2 \times 10^{15} T^{3/2} \exp\left(\frac{-E_g}{2KT}\right)$$

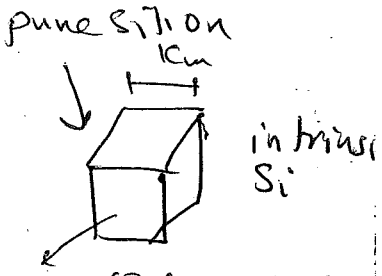
n_i ↓ intrinsic

Eg: bandgap Energy

K: Boltzman Const $= 1.38 \times 10^{-23}$ J/K

$E_g = 1.12$ eV for Si
$= 0.67$ eV for Ge
$= 5.5$ eV for Diamond

(4) Example: For Si at T = 300 K



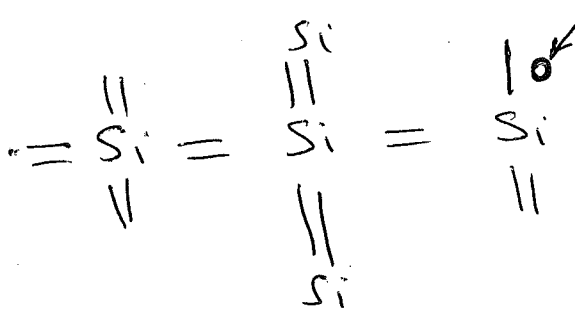
$n_i \cong 10^{10}$ electron/cm^3

We see 1 cm^3 Si $\longrightarrow$ 5×10^{22} Si atoms/cm^2

and 10^{10} free electron (small number)

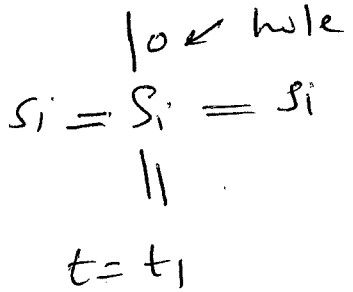
$\Rightarrow$ pure conductor

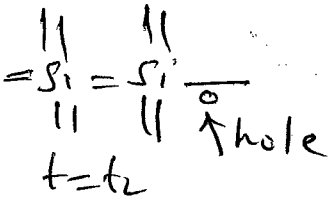
Concept of Holes:



If the atom of silicon missing an electron it create a hole with positive charge

If we take a snapshot after few





We see one hole move from left side to right side

$\Rightarrow$ positive charge " "

So the hole can create ~~electric~~ current

$\Rightarrow$ positive current

Question: Why holes slower than electrons?

the way of moving of holes are realse then trap. but for electron

⑤ Movement of holes based on release and trap mechanisms.

Density of holes = Density of electrons = n_i
for pure Silicon (intrinsic)

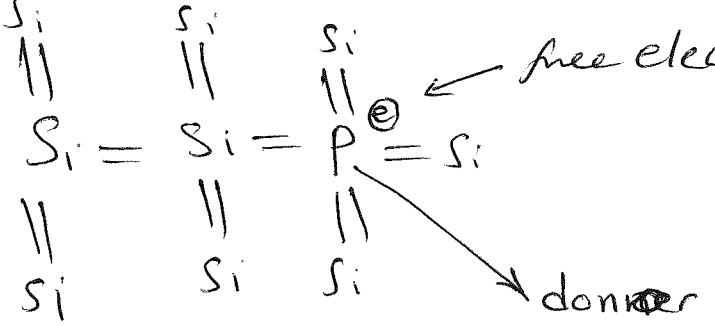
$$p = n = n_i$$

$$pn = n_i^2$$

Doping: How to modify the density of charge in semiconductor?

III	IV	VA V
Boron (B)		
	Si	phosphorus (P)
	Ge	

Extrinsic Si



n-type Si

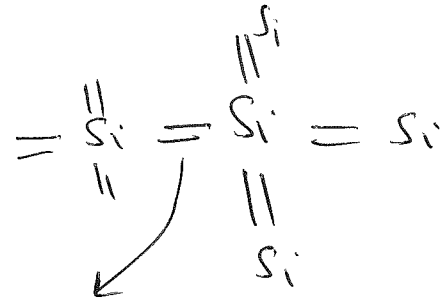
N_d = Density of P atoms = $10^{15} - 10^{17}$ cm^{-3}

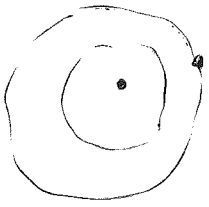
$n \cong$ density of P atoms = N_d

$$np = n_i^2$$

Lect 2

Review of first lecture





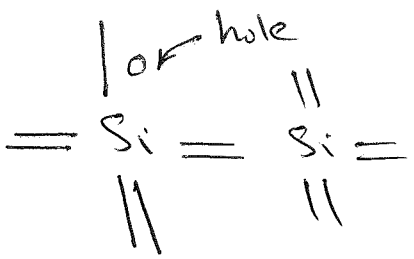
Si = 4e

$$n_i = 5.2 \times 10^{15} T^{3/2} \exp \frac{-E_g}{2kT}$$

$E_g = 1.12\,eV$ for Si

$n_i = 10^{10}$ @ $T = 300\,K$

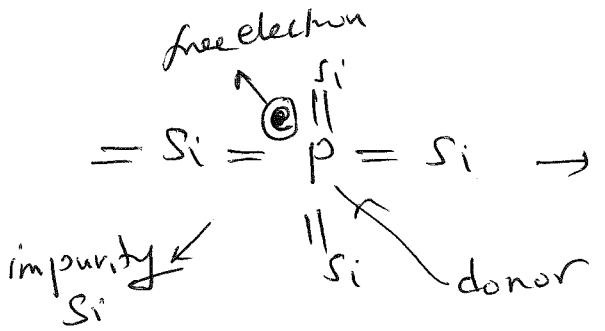
Holes



of free electron = n_i

of holes = n_i

Doping



→ n type

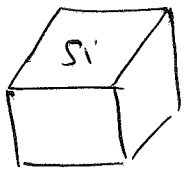
Today's lect

- Doping [n type and p-type] semiconductor
  - Modified carrier densities
- Movement of charge (carrier transports)
  - Drift
  - Diffusion

Doping:

- If we add N_d donor atoms, then the density of free electrons $= N_d / cm^3$
- n: density of free electrons
  p: density of holes.
- for pure Silicon $\quad n = p = n_i$
  $np = n_i^2$
- For dopped Si
  $np = n_i^2$
- for n-type Si $\Rightarrow n \approx N_D \Rightarrow p = \frac{n_i^2}{N_D}$.

Example:



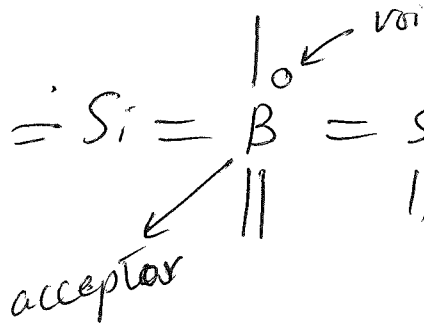
Add 10^{15} phasphorus atoms

$\Rightarrow n = 10^{15}/cm^3 = N_D$

$p = \frac{n_i^2}{N_D} = \frac{10^{20}}{10^{15}} = 10^5/cm^3$

$\Rightarrow$ In n-type $\begin{cases} n \longrightarrow \text{majority} \\ p \longrightarrow \text{minority} \end{cases}$

Can holes become majority carriers?



p-type Semiconductor

If we add N_a boron atom per cm^3
$\Rightarrow$ we have N_a holes

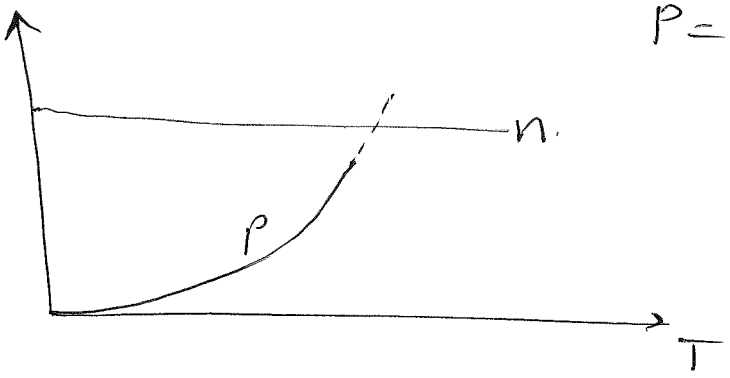
number of hole $p = N_a$

$$np = n_i^2 \Rightarrow n \cong \frac{n_i^2}{N_a}$$

Quiz: What happens to n and p in n-type Si as T increases?

$n = N_D$.

$p = \frac{n_i^2}{N_D}$.

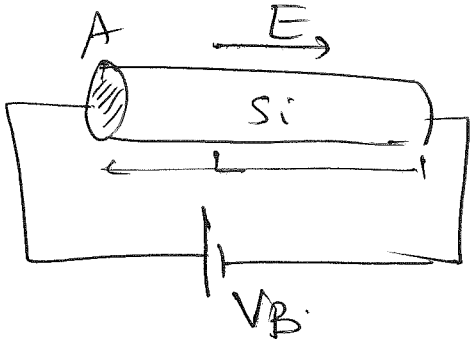


Summary

n-type	P-type
(electron) $n = N_d$ $(10^{15} \sim 10^{17})$	$p = N_a$ (hole)
$p = \frac{n_i^2}{N_d}$	$n \cong \frac{n_i^2}{N_a}$
n: majority	p: majority
p: minority	n: minority

* Carrier Transport → Drift
                    → Diffusion

1) Drift :-



Drift : current conduction due to electric field.

Ohm Law $V = IR$ $\quad R = \rho \frac{L}{A}$ (ρ: resistivity)

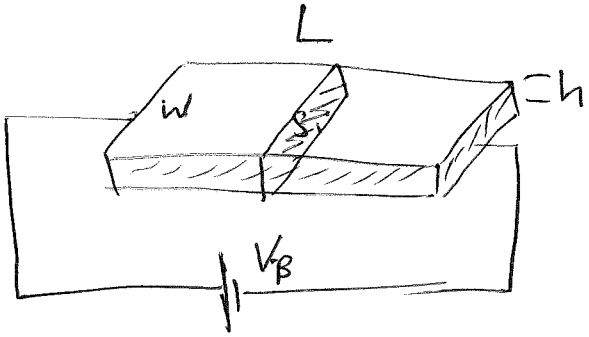
$v \propto E$

v velocity of electron

$v = \mu_n E$ $\quad \mu_n$: mobility of electron

$\mu_n = 1350$ ~~cm/V.s~~ $cm^2/(V.s)$ unit: second

Observation :-



electric field $E = \frac{V_B}{L}$

Current : is defined as the charge passing a cross section in 1 sec

Total charge $= vWhnq = |I|$ current

$I = \mu_n \frac{V_B}{L} Whnq$

$R = \frac{L}{\mu_n Whnq} = \rho \frac{L}{A} \Rightarrow$ ~~R~~

$$R = \underbrace{\frac{1}{\mu_n n q}}_{\rho} \frac{L}{A}$$

$$\text{Current density} = \frac{I}{A} = \mu_n \frac{V_B}{L} n q$$

$$J_n = \mu_n E n q \quad A/cm^2$$

Total Current Density

$$\text{(Drift Current)} \quad J = (\underbrace{\mu_n n q}_{\text{electron}} + \underbrace{\mu_p p q}_{\text{hole}}) E$$

$$\mu_p \cong 400 \ cm^2/(V \cdot s)$$

lect 3.

Today's lecture

* Current Transport by diffusion
* Pn Junction
  * Application
  * Basic Structure
  * Behaviour in Equilibrium

Review:

Doping

n-type

majority → e

minority → h

Si
Si
Si

$n \cong N_D$

$p = \frac{n_i^2}{N_D}$

P-type

majority h

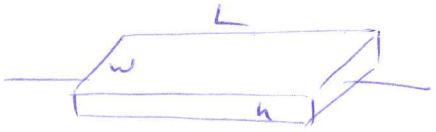
minority e

hole

$p = N_a$

$n = \frac{n_i^2}{N_a}$

Carrier Transport

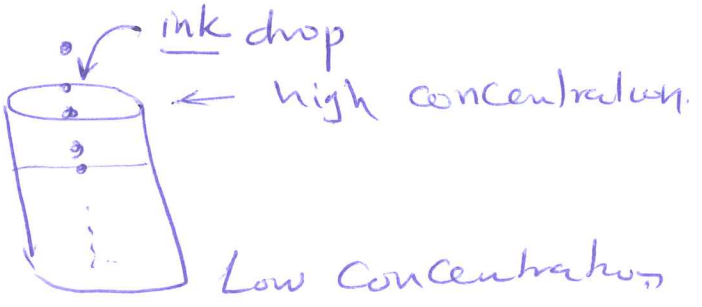


Drift Current

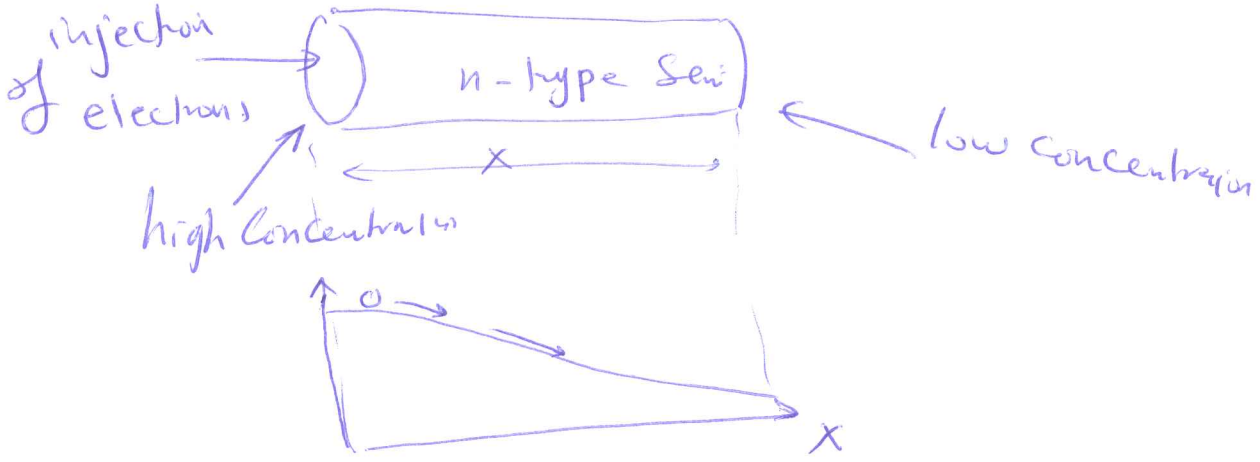
$v = \mu E$ | IE. ohm q

$\Rightarrow J = (\mu_n n + \mu_p p) q E$

* Diffusion:



Diffusion: : movement of charge carriers from region of high concentration to a region of low concentration.



$$J \propto \frac{dn}{dx}$$

$$J_e = D_n \frac{dn}{dx} \cdot q \qquad D_n : \text{diffusivity}$$

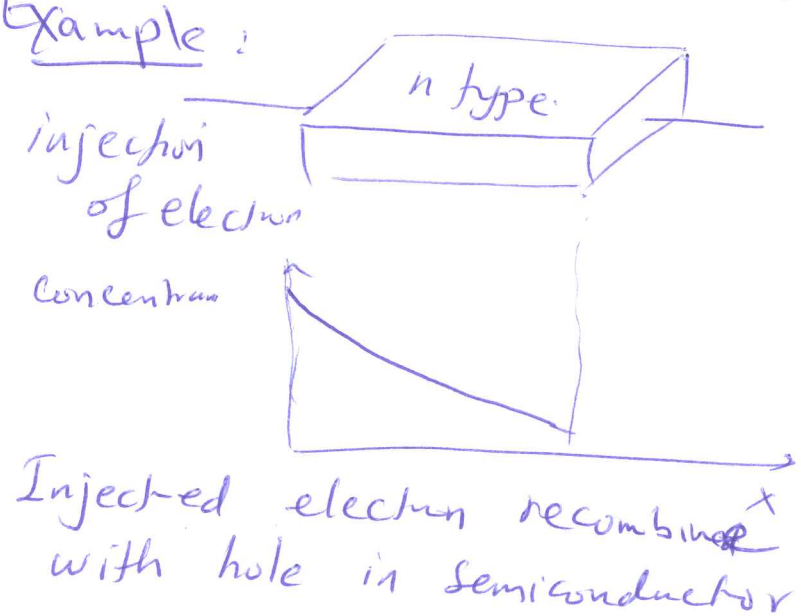
for hole

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

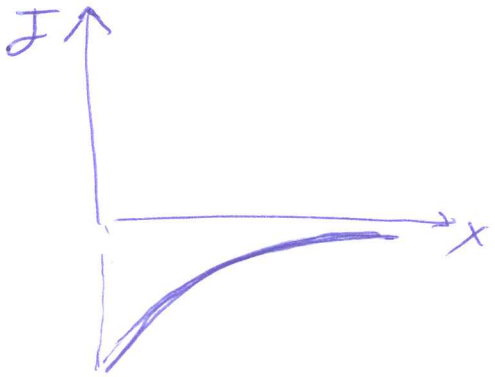
In general, $J_{total} = \left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx}\right) q$ ← electron charge

$D_n = 34\ cm^2/sec$, $D_p = 12\ cm^2/s$

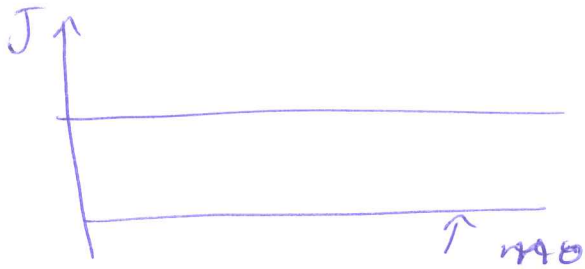
Example :

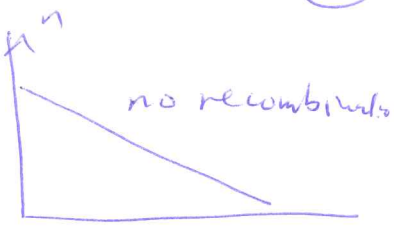


Plot → diffusion the current



If there are no recombination





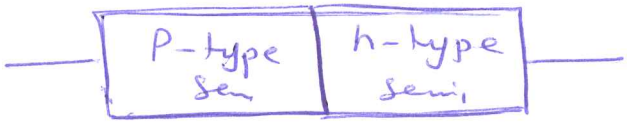
Einstein's Relation:

$$\frac{D}{\mu} = \frac{kT}{q} = 26\,mV$$

↑ thermal voltage

∂ room temp. $T = 300K$

The pn Junction:

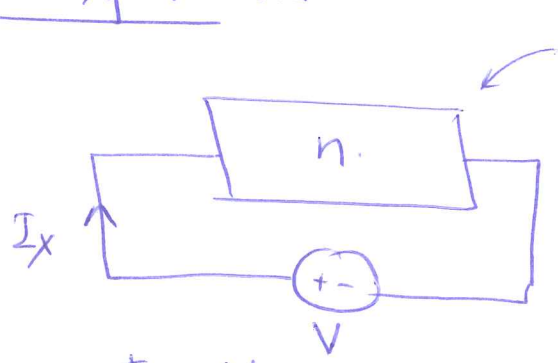


two terminal device Called (diode)

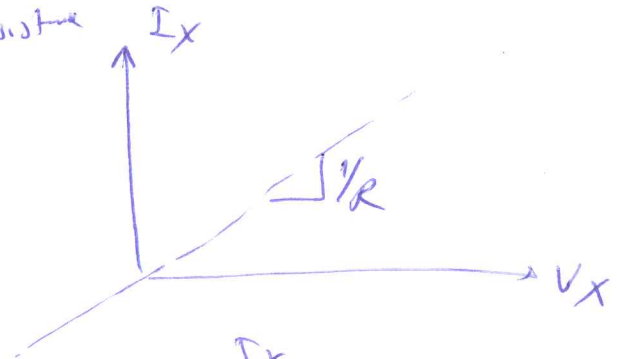
Applications

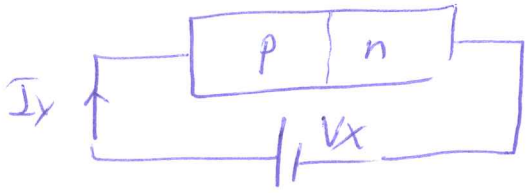
- Charger and adaptors
- Voltage multipliers

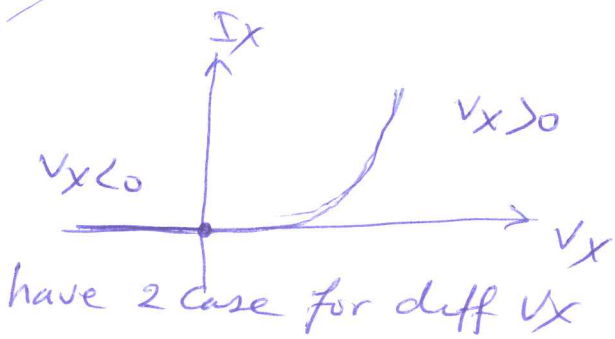
Quick Experments



$$I_x = \frac{V_x}{R}$$







have 2 case for diff V_x

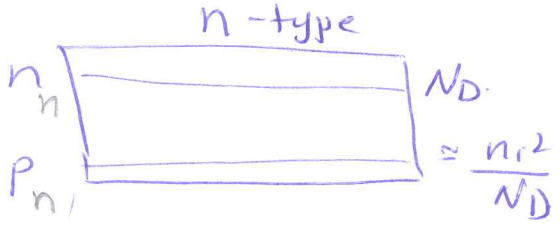
Two Questions:

1) How do the charge carriers redistribute themselves after the pn junction is formed?

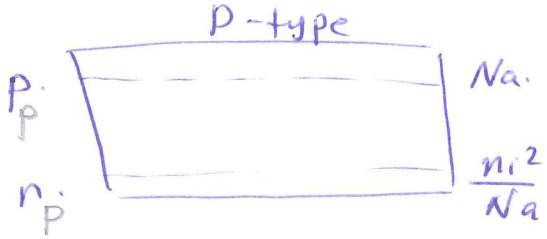
2) How does the pn junction behave under three conditions:
   - Equilbrium
   - Reverse Bias
   - forward Bias

Some Observations:

1)

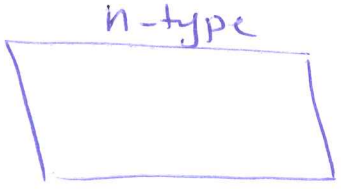


majority is electron



majority hole

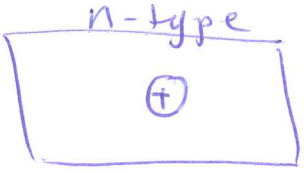
2)



← what is the net charge in this device

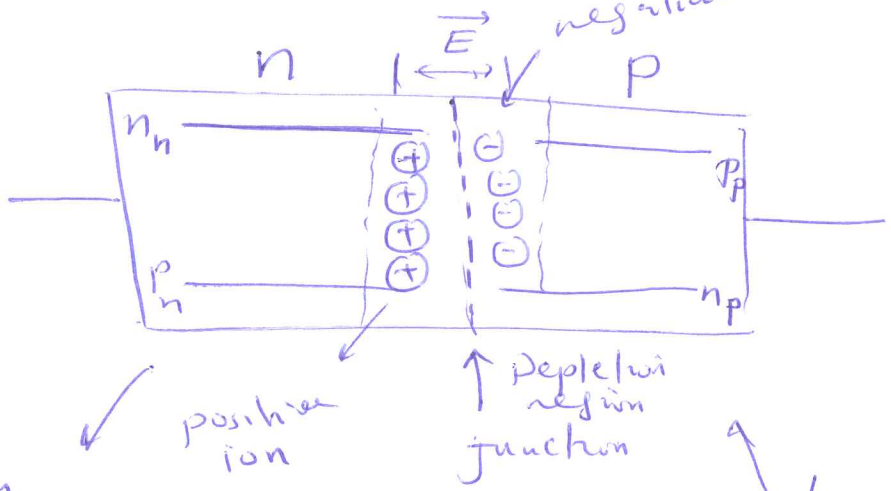
⇒ Charge neutality

3)



if we take 1 electron out of the device ⇒ a positive ion is formed.

• Pn Junction in Equilibrium



positive ion

Depletion region
junction

high Concentration of electron

low Concentration of hole

low concentration of electron

high concentration of hole

lect 4 :

Today's lect

- Pn junction in Equilibrium
- Pn Junction in Reverse Bias

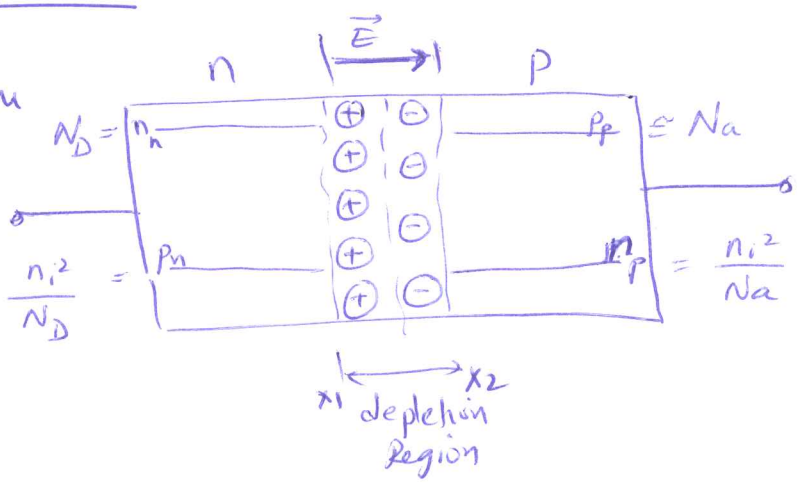
Review:

Current Conduction:

* $J_{drift} = (\mu_n n + \mu_p p) E q$
* $J_{diffusion} = \left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx}\right) q$

PN Junction

Equilbrium (no Bias)



- Since there are electric field created due to the positive and negative ions, ⇒ Equilbrium Condition:-
So that ⊛ diffusion current of electron = drift current of elect
⊛ diffusion current of holes = " " = holes

For hole :

$$D_p \frac{dp}{dx} q = \mu_p p E q$$

$$D_p \frac{dp}{p} = \mu_p E \, dx$$

$$\int_{p_n}^{p_p} D_p \frac{dp}{p} = \mu_p \int_{x_1}^{x_2} E \, dx$$

Remember: $-\int_a^b \mathcal{E}\,dx = V(a) - V(b)$

$$\Rightarrow \quad D_p \ln \frac{P_p}{P_n} = \mu_p \left[V(x_1) - V(x_2) \right]$$

$$= \mu_p V_o$$

$$V_o = \frac{D_p}{\mu_p} \ln \frac{P_p}{P_n}$$

$$V_o = \frac{D_p}{\mu_p} \ln \frac{N_a N_d}{n_i^2} = \frac{KT}{q} \ln \frac{N_a N_d}{n_i^2}$$

V_o: is called the built in potential.

$\frac{KT}{q} = 26\,mV$ @ 300K (room temp)

Quiz:- Is there an electric field outside the depletion region?

⇒ No electric field., only the electric field exist in the depletion region

⇒ the net charge = 0

⇒ Voltage drop = 0 in the neutral region

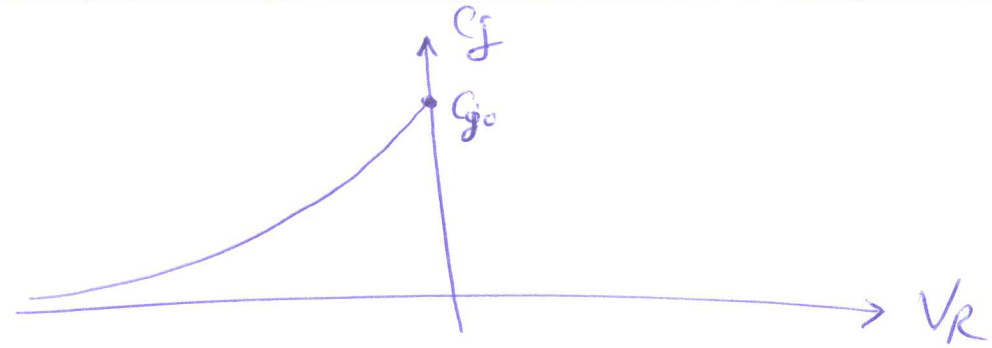
Observations:-

1) Same V_o expression is obtained if the electron currents are considered.

2) If N_a and N_d are on the order of $10^{16}/cm^3$

⇒ $V_o \cong 26\,mV \ln \frac{10^{32}}{10^{20}} \cong 720\,mV$

⇒ Typical values of V_o are from (700 – 800 mV)

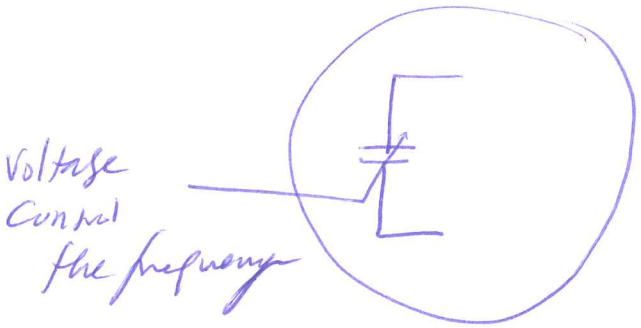


Reverse Bias

$$C_j = \frac{C_{j0}}{\sqrt{1 - \frac{V_R}{V_0}}}$$

Application

Osciallator for Bluetooth.

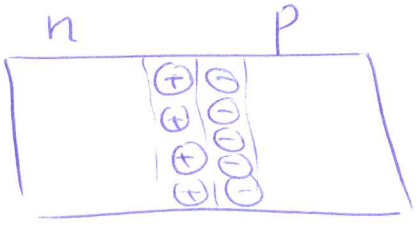


Today's lecture:

- Pn junction in forward Bias
- Modeling the pn junction
- Reverse Breakdown.

Review:

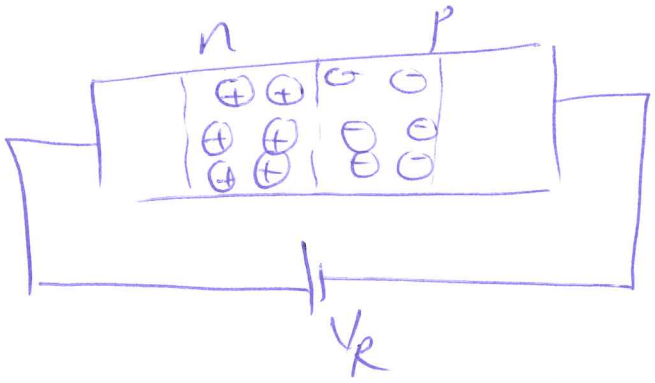
1)

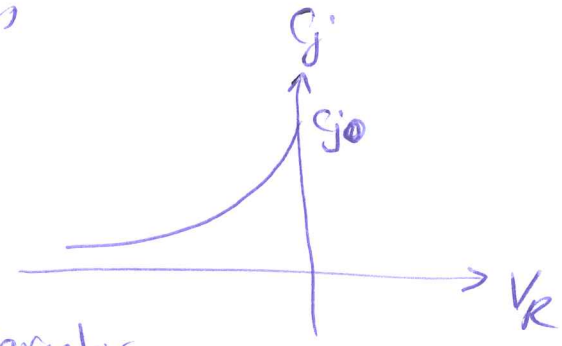


Pn junction in equilbrium

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

2) Pn junction in Reverse Bias

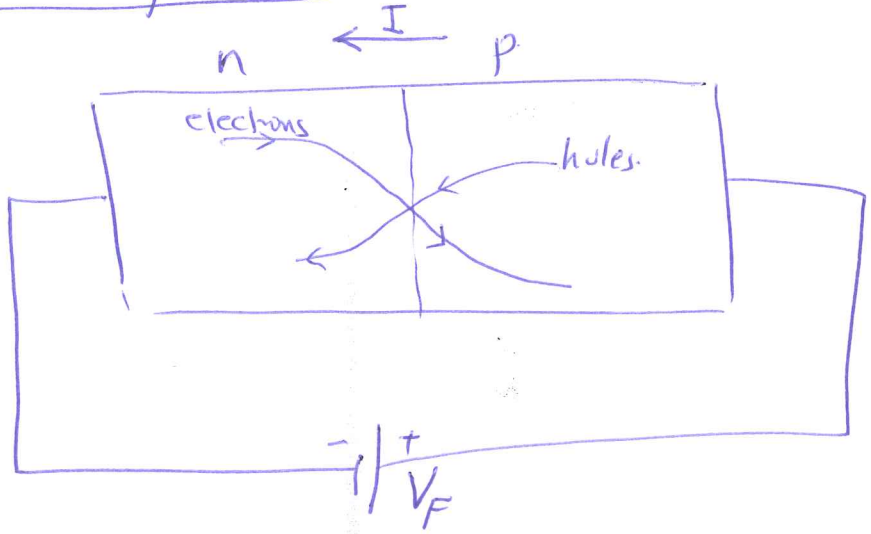


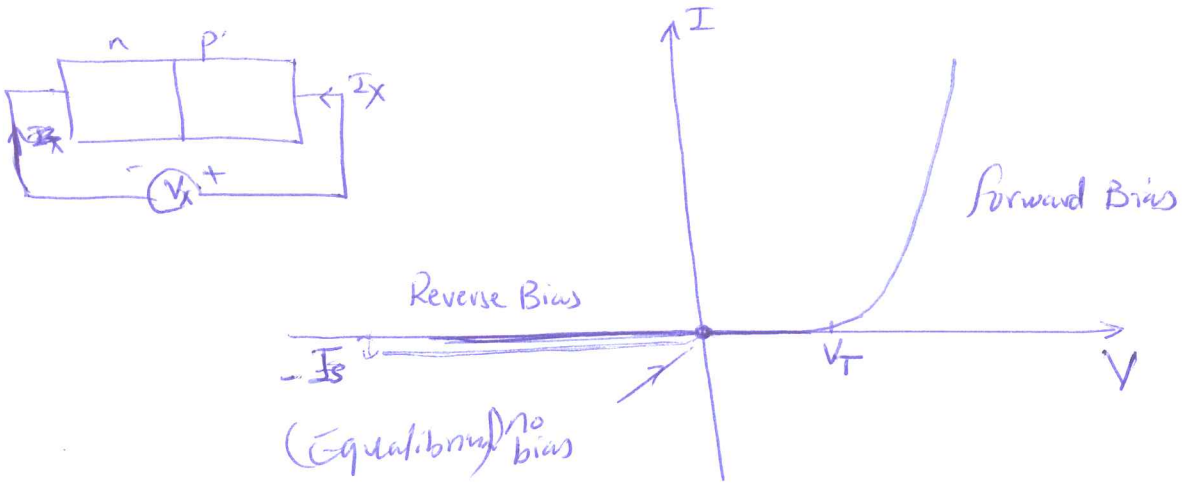


Varactor

the value changes by changing the reverse Biasing.

Pn junction in forward Bias:





$$I_X = I_{junction} = I_S \exp\left(\frac{V_X}{V_T} - 1\right)$$

Reverse
I_S: Saturation Current.

V_X: the applied voltage

$V_T = \frac{kT}{q}$ = thermal voltage (26mV)

when $V_X = 0 \Rightarrow I_X = 0$

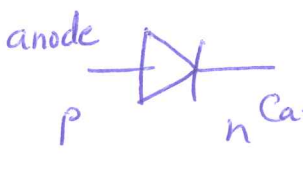
$V_X < 0 \Rightarrow I_X = -I_S$

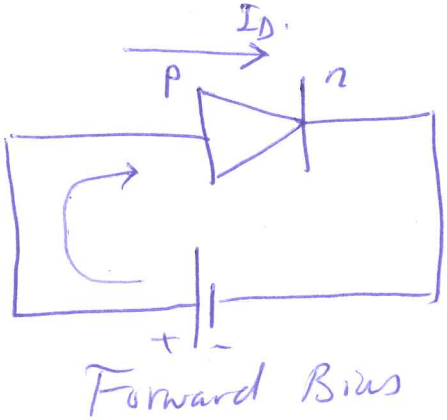
$V_X >> 0 \Rightarrow I_X = I_S \exp \frac{V_X}{V_T}$

$\Rightarrow I_D = I_S\left(\exp\left\{\frac{V_D}{V_T} - 1\right\}\right)$

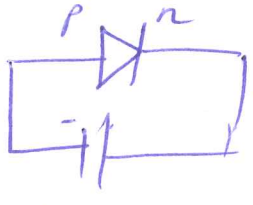
$\Rightarrow$ Diode is defined as two thermal device that carries current when its voltage is positive and no current when it voltage is negative

Symbol of diode





Forward Bias



Reverse Bias

$$I_D = I_S \exp\left(\frac{V_D}{V_T} - 1\right)$$

where

$$I_S = A \cdot q\, n_i^2 \left[\frac{D_n}{N_a L_n} + \frac{D_p}{N_d L_p}\right]$$

A: cross section Area of the junction



$I_S \propto A$ cross section Area

n_i^2 : ~~electric~~ density of e (intrinsic)

L_a / L_d : ~~deffusion~~ Diffusion length

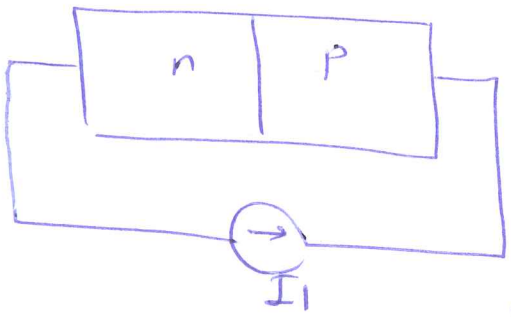
Notes:

if $\exp\left(\frac{V_X}{V_T}\right) \gg 1 \Rightarrow I_X = I_S \exp\frac{V_D}{V_T}$

$\Rightarrow$ If the forward Bias voltage $> 4 V_T \approx 104\,mV$

$\Rightarrow$ $\boxed{I_X = I_S \exp\frac{V_D}{V_T}}$ $V_T = 26mV$

Quiz:



If we injection I_1 find the voltage across the diode

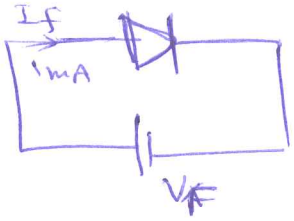
$$I_1 = I_S \exp\frac{V_D}{V_T}$$

$$\boxed{V_D = V_T \ln\frac{I_1}{I_S}}$$

Forward Bias

Example:

a) Assume $I_S = 10^{-16} A$ and we measure a forward Bias current of 1mA. What voltage is appliead to the diode?



$$V_F = V_T \ln \frac{I_F}{I_S}$$

$$= 26mV \ln \frac{1mA}{10^{-16}} \cong 778\,mV$$

b) If the current increase by a factor of 10, How much should the voltage increase?

$$V_{F_1} = V_T \ln \frac{I_1}{I_{S_1}}$$

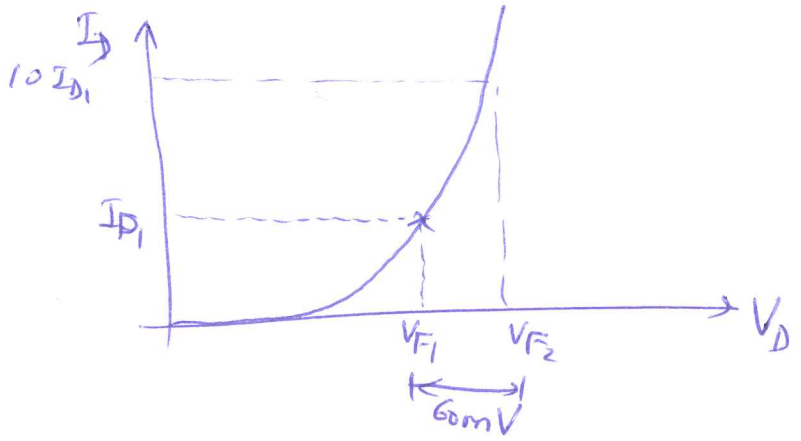
$$V_{F_2} = V_T \ln \frac{I_2}{I_S}$$

$$V_{F_2} - V_{F_1} = V_T \ln\left(\frac{I_2}{I_1}\right) \qquad \text{for } I_2 = 10 I_1$$

$$= V_T \ln 10$$

$$= 60\,mV$$

The voltage has to increase by 60 mV.

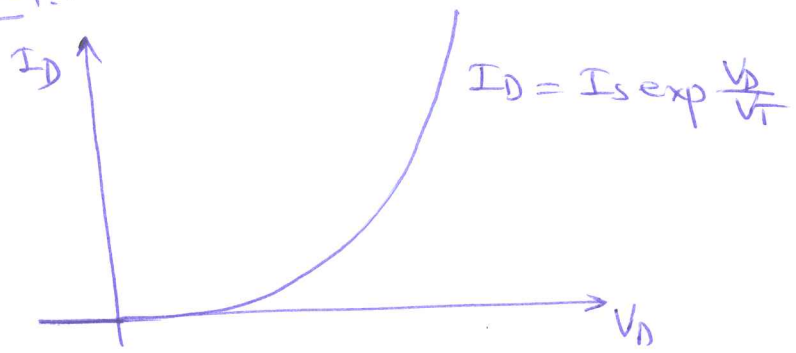


Typical forward Bias voltages for diodes are in the range of 700 – 800 mV.

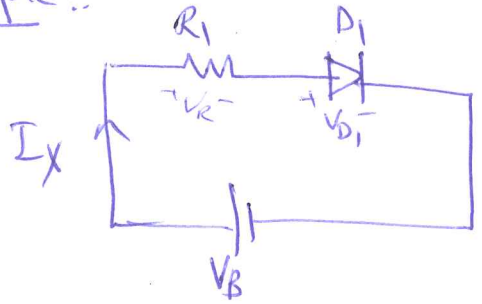
Modeling of pn junction (diode):



xi) Exponential model:



example:



Find the current I_X in the circuit

- Look to the Biasing (forward, Reverse) ⇒ forward Bias
- Assume the diode is ON (forward Biased)
- Write KVL for the circuit:

$$V_B = V_R + V_{D_1}$$
$$= I_X R_1 + V_T \ln \frac{I_X}{I_S}$$

Solving to find I_X:

making guess to solve the equation

⇒ the equation is not easy to solve

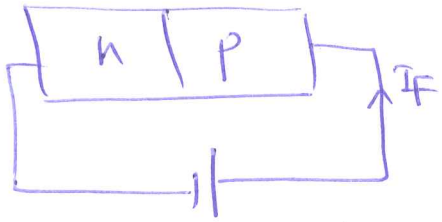
so we must look to new model to simplify the ~~R~~ solution.

Today's lecture

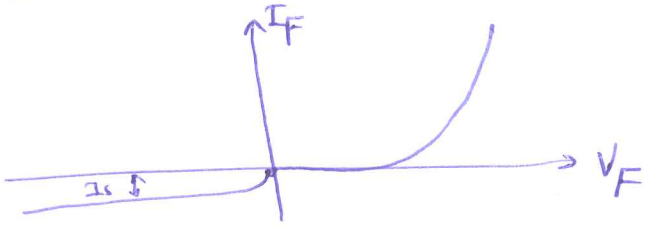
- Diode Models
- Reverse Breakdown
- Circuit Examples

Review:

- Pn junction in forward Bias

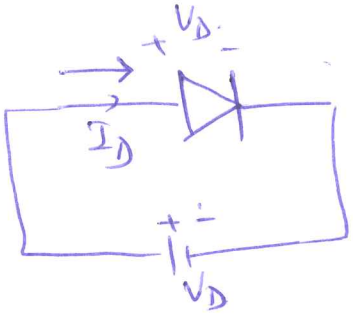


$$I_F = I_S \exp \frac{V_D}{V_T}$$



As 10X increase in I_F for 60mV increase in V_F

Diodes



$$I_D = I_S \exp \frac{V_D}{V_T}$$

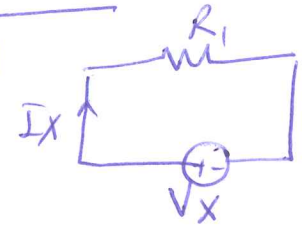
$$V_D = V_T \ln \frac{I_D}{I_S}$$

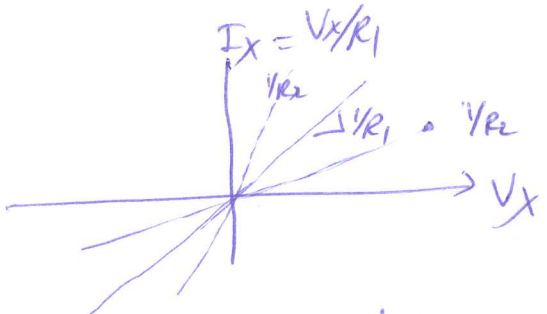
Diode Models:

- Constant voltage model:-

Observations

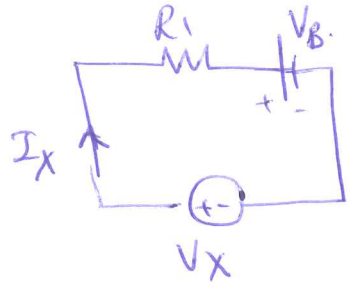
1)





as R_1 increase → the slope decrease
R_1 decrease → the slope increase until the slope becomes vertical line

2)

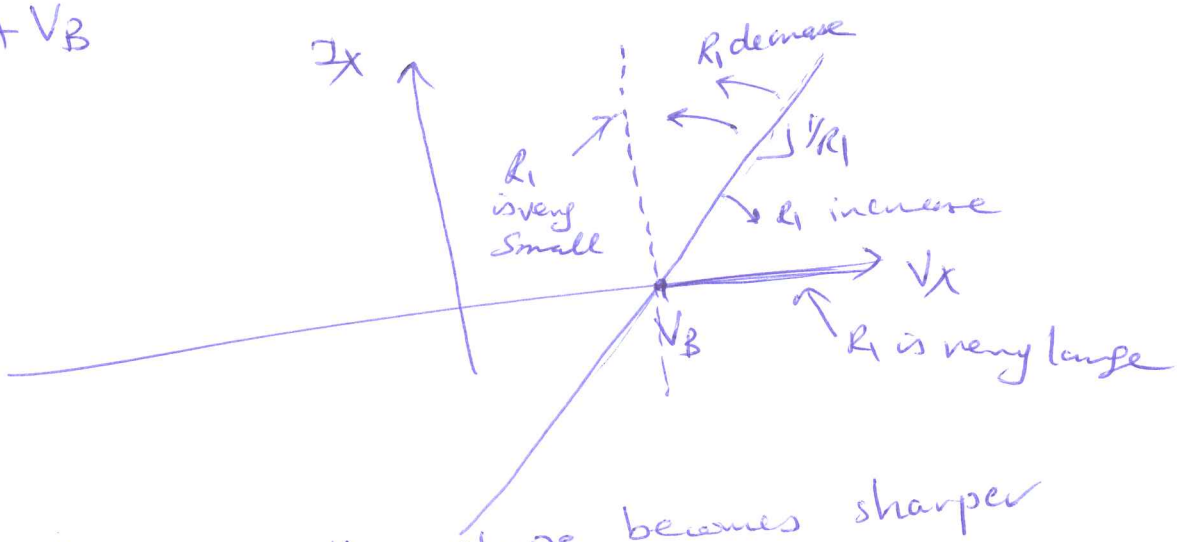


$$I_X = \frac{V_X - V_B}{R_1}$$

when $V_X = V_B \Rightarrow I_X = 0$

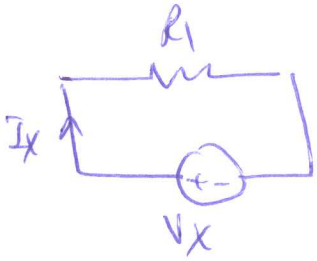
for $V_X > V_B \Rightarrow I_X > 0$

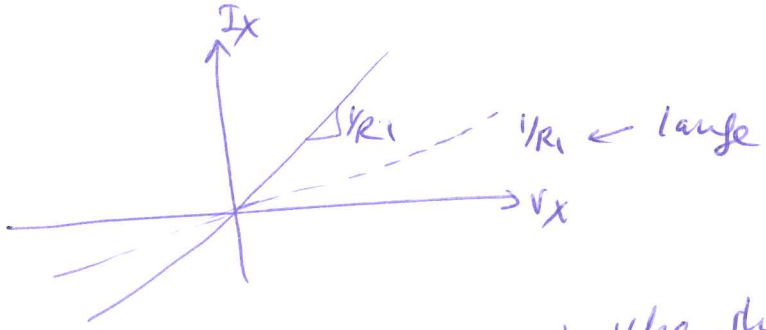
$V_X = I_X R_1 + V_B$



As R_1 decrease the slope becomes sharper

3)





- As R_1 becomes extremly large ⇒ the slope becomes horizontal
- As R_1 becomes extremly small the slope becomes vertical

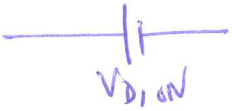
Constant Voltage Model:







If $V_X < V_{D,ON} \Rightarrow$ D is off $\Rightarrow$ 

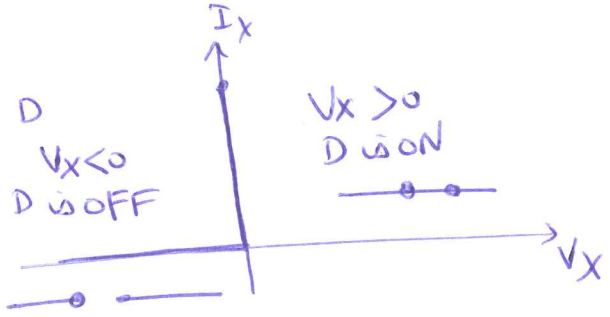
If $V_X > V_{D,ON} \Rightarrow$ D is ON $\Rightarrow$ 

wants to exceed $V_{D,ON}$

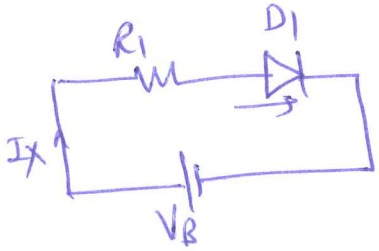
$$V_{D,ON} \approx 700 - 800mV$$

Ideal Diode Model

Ideal Diode is passing positive voltage and is stoping negative voltage

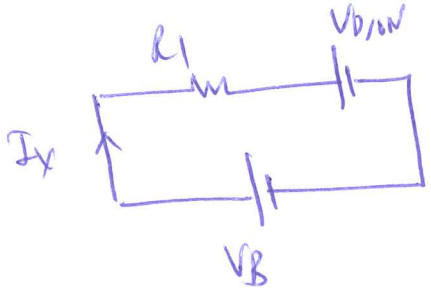


Example,



Find I_X if D is voltage constant model.

- D is forward
- Replacing diode by its equivalent circuit $\Rightarrow V_{D,ON}$



- find I_X

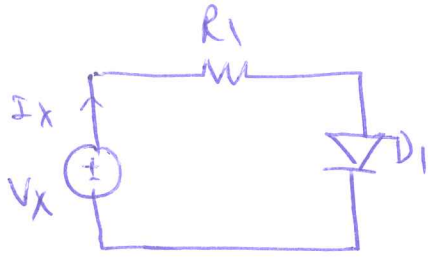
$$V_B = I_X R_1 + V_{D,ON}$$

$$I_X = \frac{V_B - V_{D,ON}}{R_1}$$

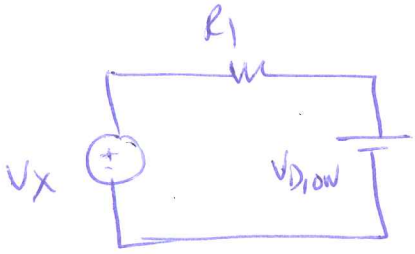
If $V_B = V_{D,ON} \Rightarrow I_X = 0$

If $V_B > V_{D,ON} \Rightarrow I_X = \frac{V_B - V_{D,ON}}{R_1}$

Quiz:



If V_X varies from $-\infty, \infty$ plot I_X, assuming D is a (constant) voltage ~~cut~~ model



Solution

- D is ON
- Replacing D by V_{D1ON}
- write the I_X equation

$$I_X = \frac{V_X - V_{D1ON}}{R_1}$$

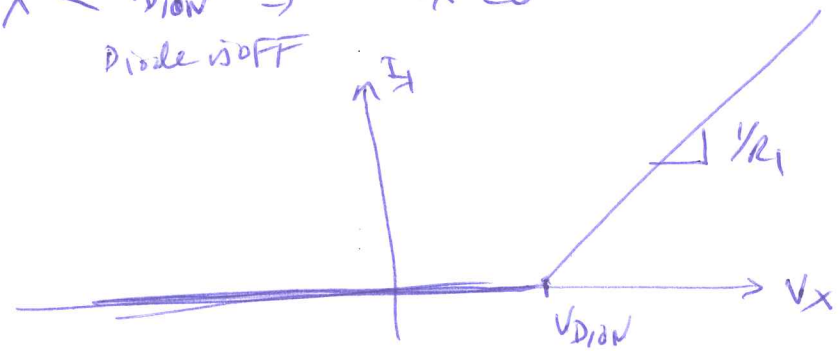
Since D is unidirection device (pass current in one direction)

If $V_X = V_{D1ON} \Rightarrow I_X = 0$

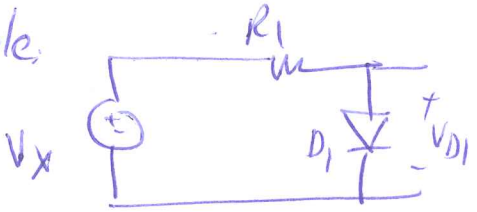
$V_X > V_{D1ON} \Rightarrow I_X = \frac{V_X - V_{D1ON}}{R_1}$

$V_X < V_{D1ON} \Rightarrow I_X = 0$

Diode is OFF



Example:



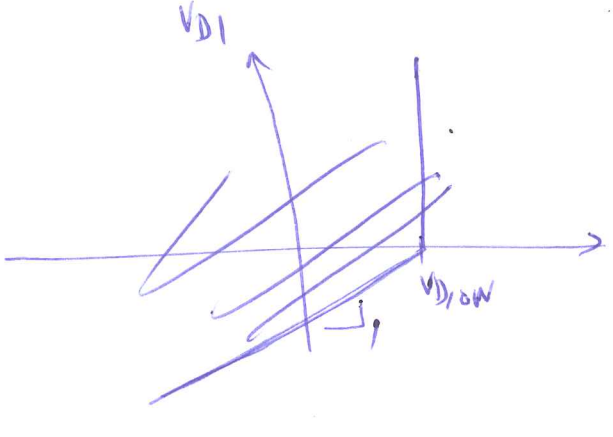
sketch V_{D1} for voltage constant

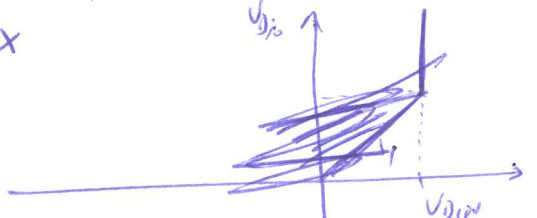
- D is ON in ⊕ region
- Transition level

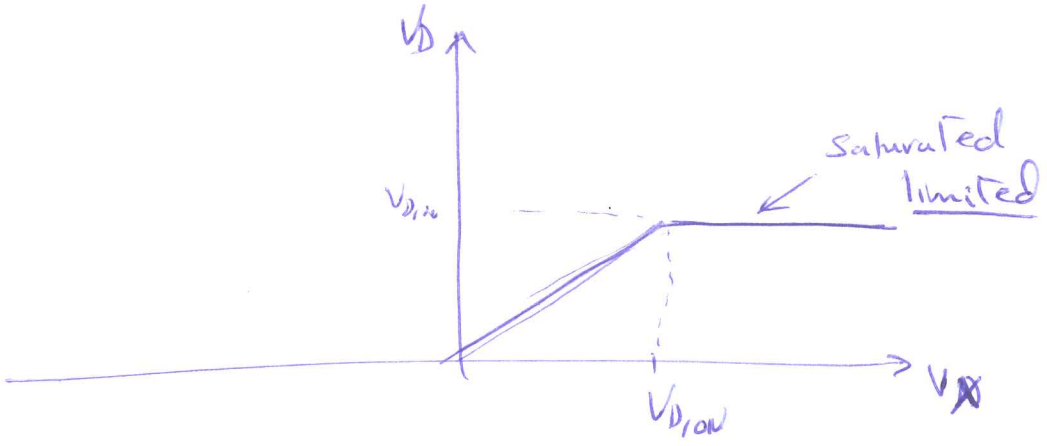
$$I_X = \frac{V_X - V_{D1ON}}{R_1}$$

If $V_X \geq V_{D1ON} \Rightarrow D_1$ is ON $\Rightarrow V_{D1} = V_{D1ON}$

$V_X < V_{D1ON} \Rightarrow D_1$ is OFF $V_{D1} = V_X$

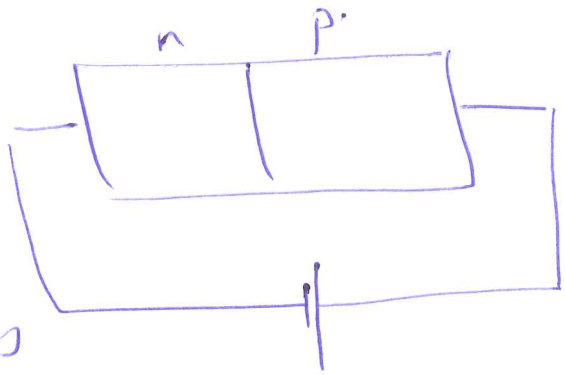




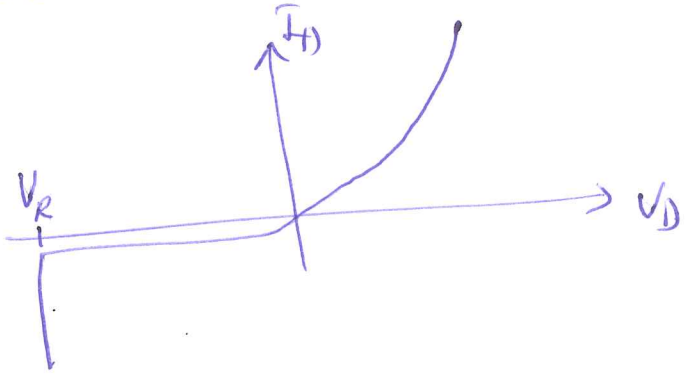


* Reverse Breakdown :

- 3 region of operation of diode
  - No bias.
  - forward Bias
  - Revere Bias



- If we apply revere bias



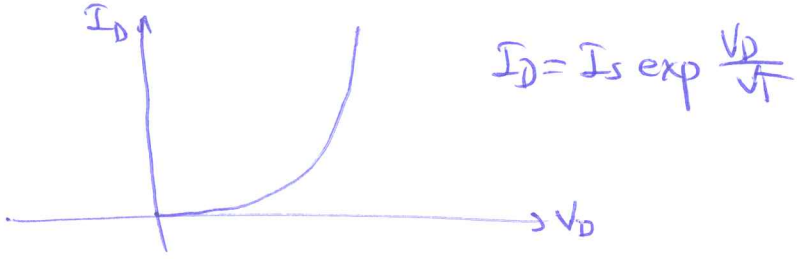
Today's Lecture

- Summery of Diode Models
- Practice with diode Circuits

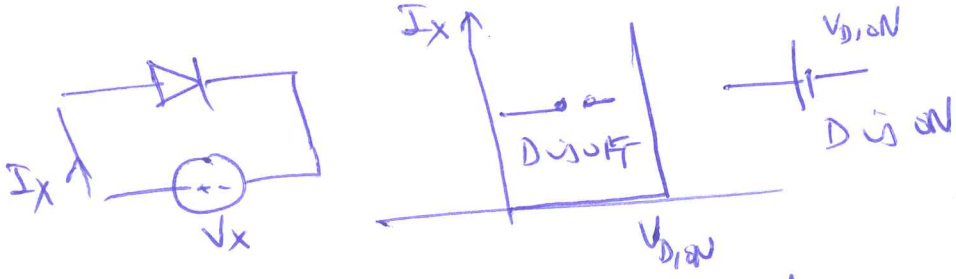
Review:

Diode Models:

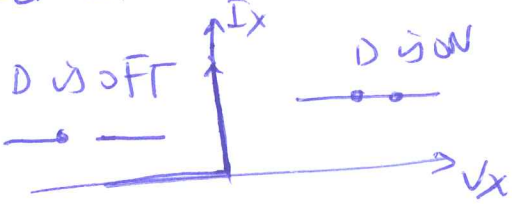
1) Exponential diode Model



2) Constant Voltage Model



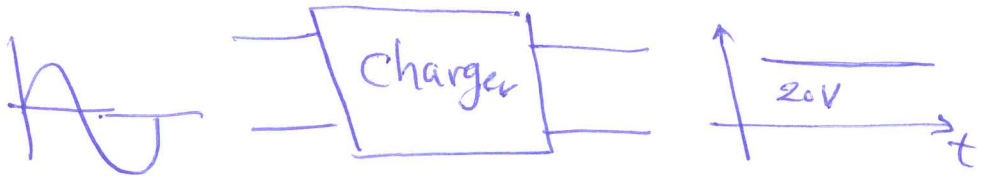
3) Ideal diode model



Diode Models (Exp, Const, Ideal)

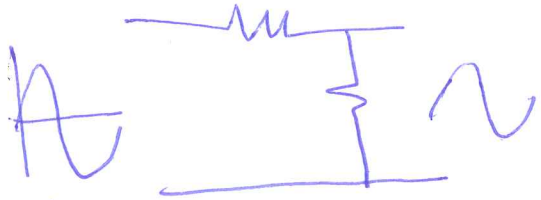
- All three models are non linear
- All three model distiguish between (+) and (-) Voltages (Rectification)
  - The ideal model passes positive voltages
  - The constant " " Voltage greater than $V_{D_{ON}}$
  - The exp model " " Voltage Siginfically if $V_D >$ 700 mV 800

Application Example (charger/Adapter)



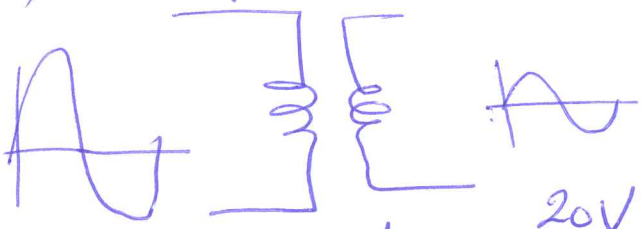
110V
60 Hz
ac

dc

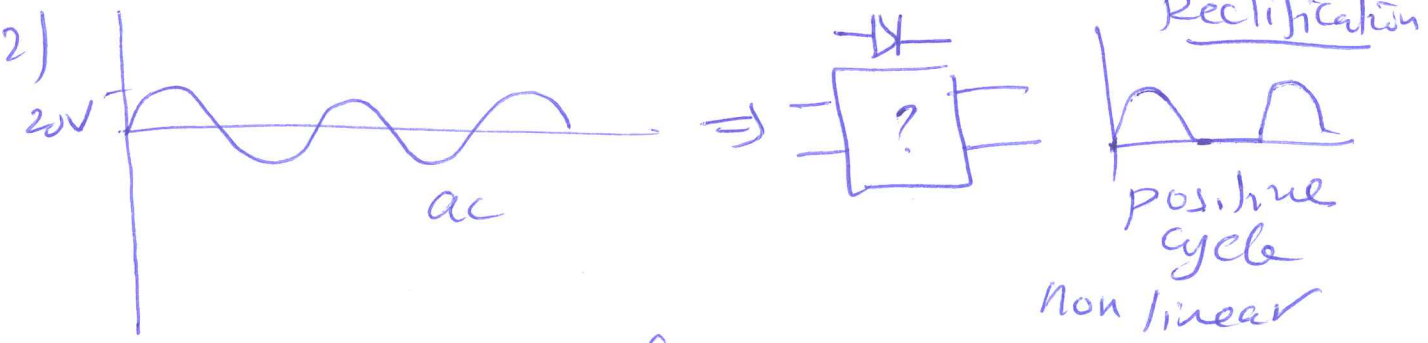


don't use voltage divider because assume large power

1) Transformer



2)



the box is nonlinear function

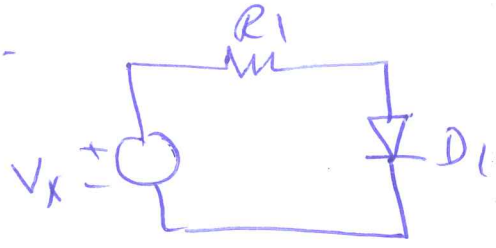
The average value of the output of box is not zero

3)



Example :-

a)



D1 is ideal

draw $I_x = f(V_x)$

where $-\infty < V_x < \infty$

Procedure :-

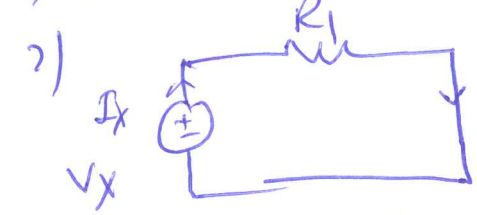
1) Assume D is ON
2) Replacing the D with its equivalent Cir
3) write the equation of the diode current
4) Set $I_D = 0$, then find the transition voltage.
5) Study the two cases.
6) Complete the solution

Solution:

1) D is ON

$I_x = I_{D1}$

2)



$I_x = \frac{V_x}{R_1}$

V_T (Transition Voltage)

$V_T = 0$

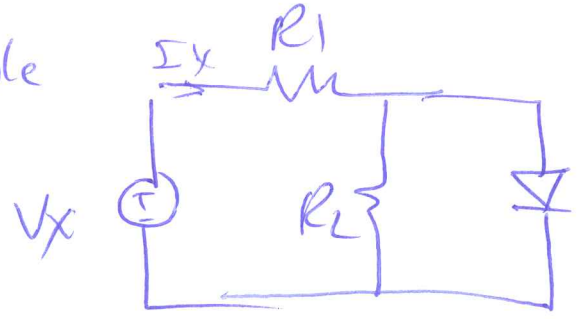
when $V_x \leq 0 \Rightarrow$ D is OFF

$\Rightarrow I_D = 0$.

when $V_x > 0 \Rightarrow$ D is ON $\Rightarrow I_x = \frac{V_x}{R_1}$



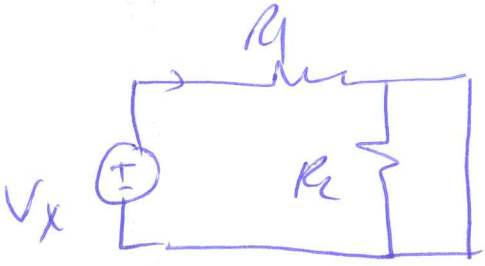
Example



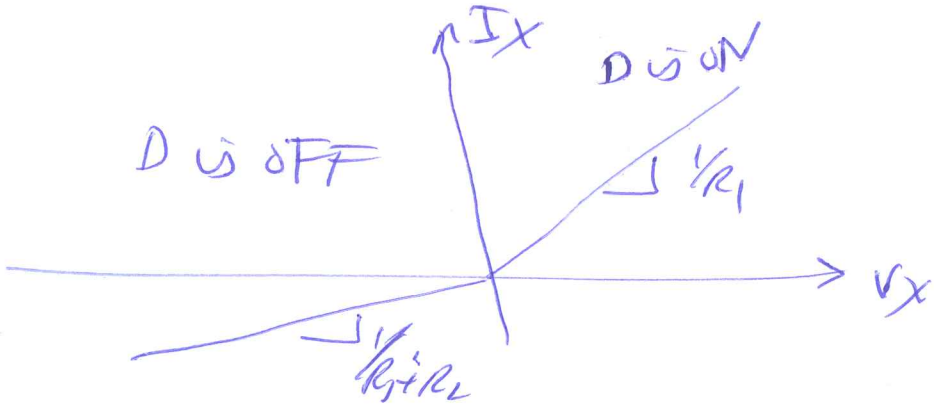
D is ideal

Draw $I_x = f(V_x)$.

- Assume D is ON
- Replace D by short cut.

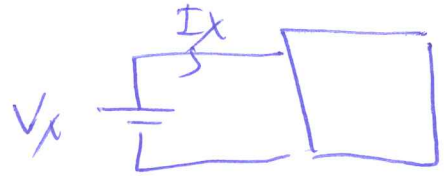


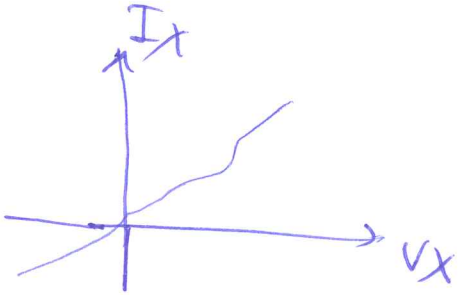
- $I_x = \frac{V_x}{R_1}$ transition voltage $V_x \geq 0$
- If $V_x \geq 0 \Rightarrow$ D is ON $\Rightarrow I_x = V_x/R_1$
- If $V_x < 0 \Rightarrow$ D is OFF $\Rightarrow I_x = \frac{V_x}{R_1+R_L}$.



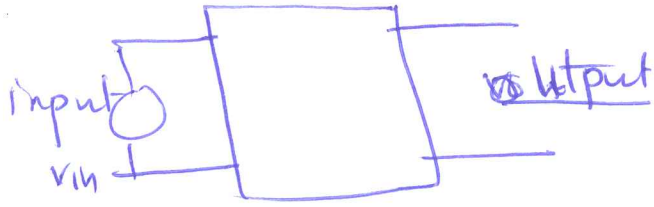
Types of Characteristics :

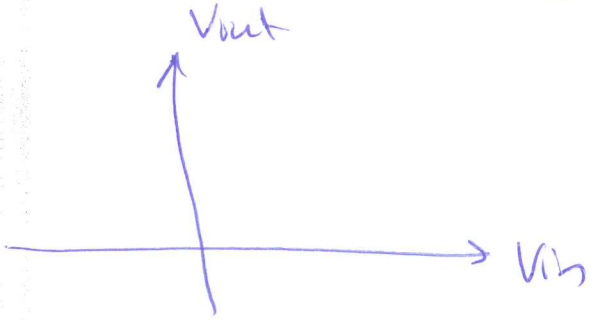
1) I-V Characteristic





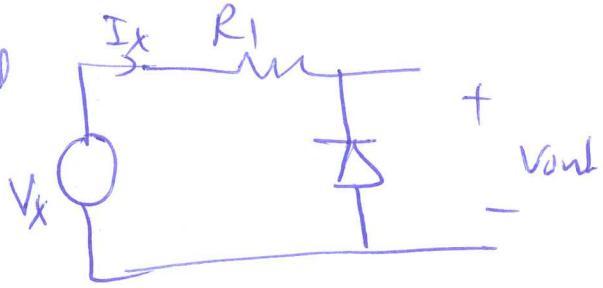
Input/output characteristic



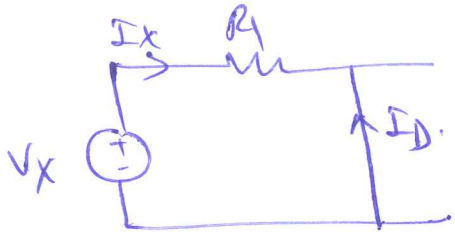


Example: plot D is ideal

1) $I_X = f(V_X)$
2) $V_{out} = f(V_X)$



- Assume D is ON



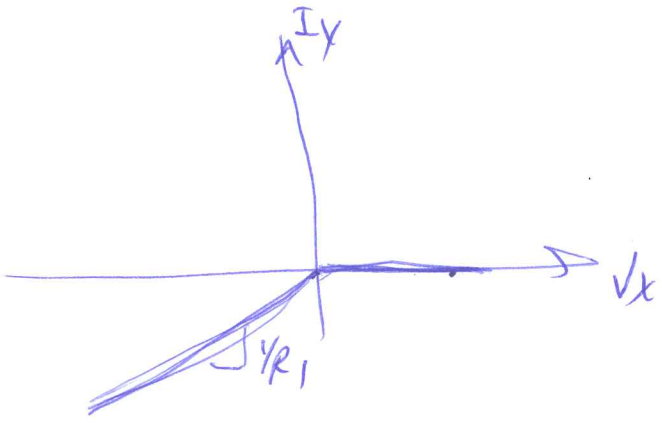
$$I_X = -I_D = \frac{V_X}{R_1}$$

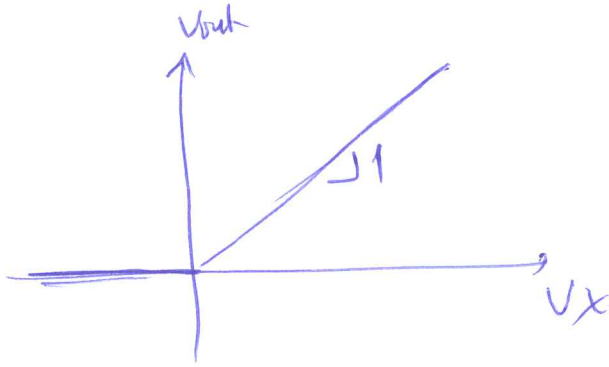
the current of diode must be ON

transition level $V_X = 0$.

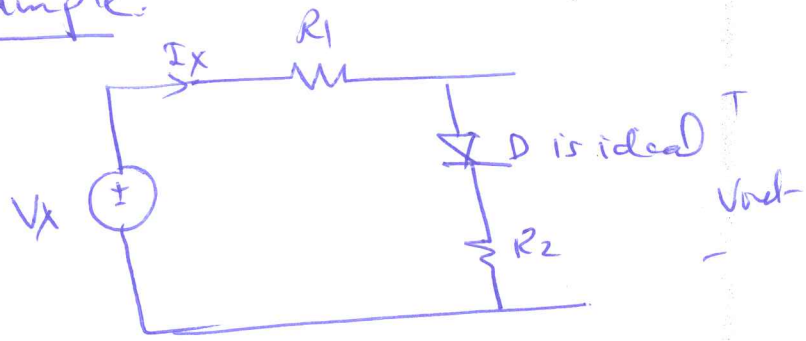
If $V_X \leq 0 \Rightarrow$ D is ON $\Rightarrow I_X = V_X/R_1 \Rightarrow V_{out} =$

If $V_X > 0 \Rightarrow$ D is OFF $\Rightarrow I_X = 0 \Rightarrow V_{out} = V_X$





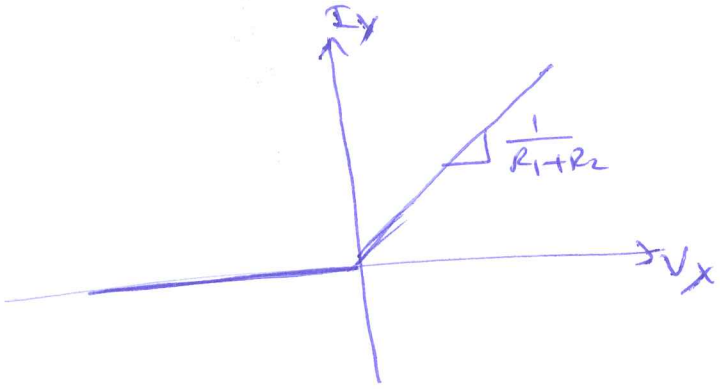
Example.

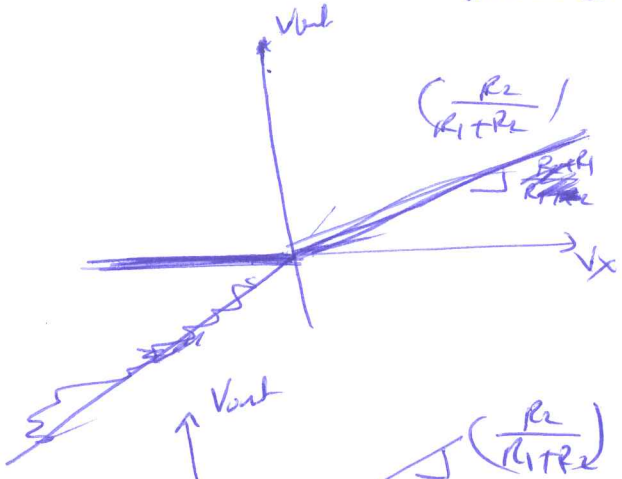


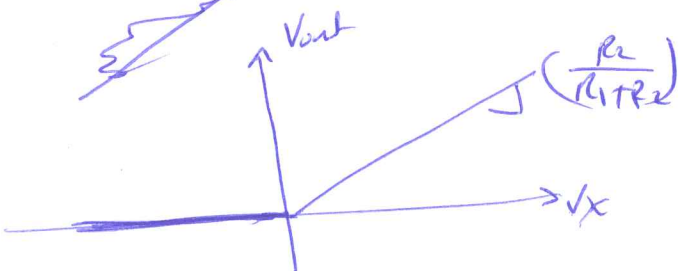
transition level $V_X = 0$

If $V_X \geq 0 \Rightarrow$ D is ON $\Rightarrow I_X = \frac{V_X}{R_1+R_2}$, $V_{out} = \frac{R_2}{R_1+R_2} V_X$

If $V_X < 0 \Rightarrow$ D is OFF $\Rightarrow I_X = 0$ & $V_{out} = I_D R_2 = 0$

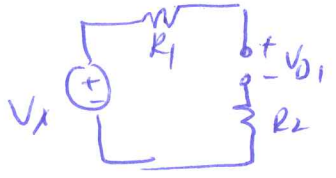


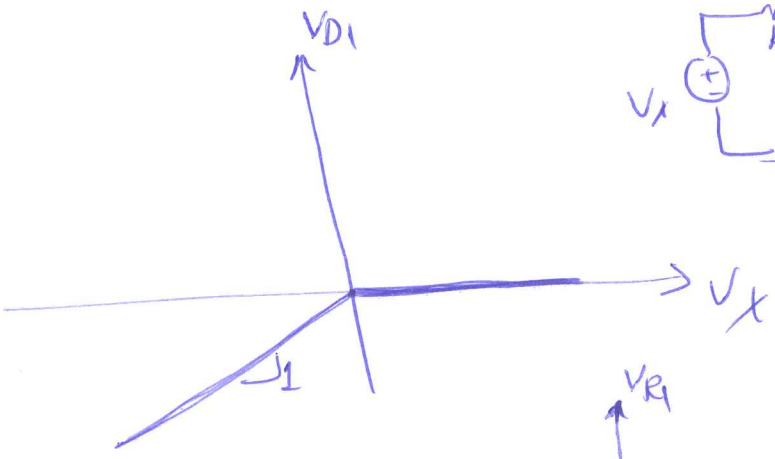


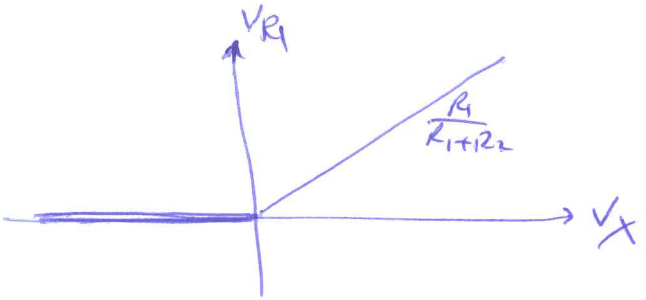


Draw V_{D1} in function $V(X)$

If $V_X < 0$. D is OFF







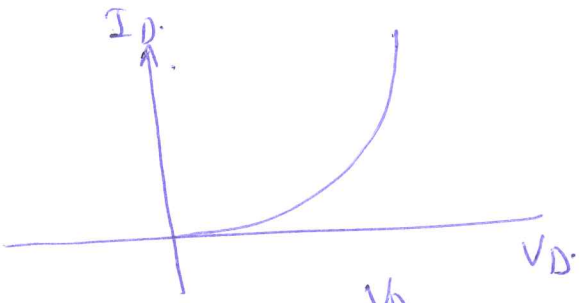
Today's lecture:

- Application Example
- Principles of diode circuit Analysis
- Example Using constant Voltage model

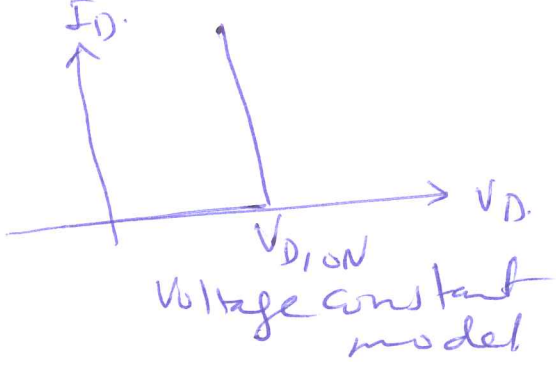
Review:

Diode has three model

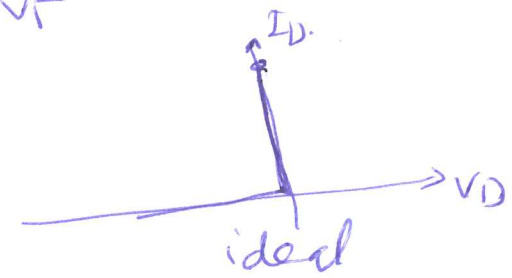
- Expensional model
- Voltage Constant model
- ideal Model



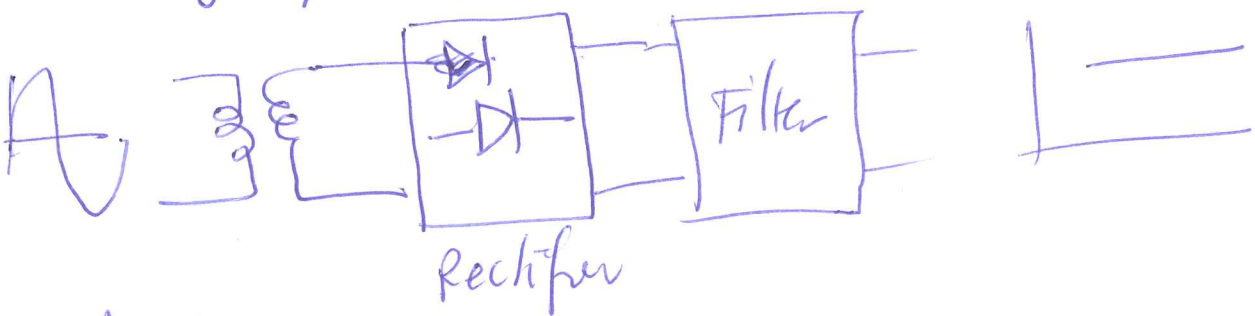
$$I_D = I_S \exp \frac{V_D}{V_T}$$



Voltage constant model



Charger / Adapter

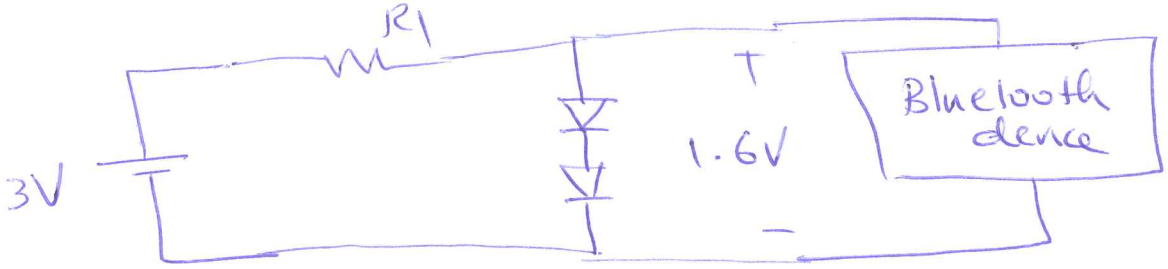


Analysis of diode circuit

- Need to assume Diode [ON, OFF]
- Must check the final Result

- Application Example:

Assume we have Bluetooth device.
To operate at 1.6V and we have battery 3V
The question how to connect the battery with the Bluetooth device.



- If we take two diode in serial it gives the voltage 1.6V
- The question how to bias the diodes
  - By adding resistance R_1
  - It is better to using diodes better than voltage divider because the ~~voltage~~
    - The voltage across each diode is a weak function of its current that means if the current fluctuate due to the voltage of the battery the current remain has less function than the voltage divider

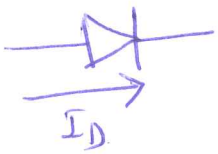
∴ The diode operate as a simple voltage regulator.

* Principles of diode Circuit Analysis

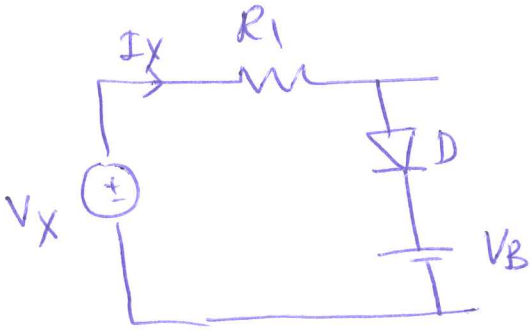
1) Begin by assuming certain state for all diodes
   Check the final result against these assumption

2) If a diode is about to turn ON or off;
   it must sustain a voltage of $V_{D,ON}$, 

   but its current is small.

3) If a diode is ON and carries a current,
   the current must flow from the anode to
   the cathode 

Example:

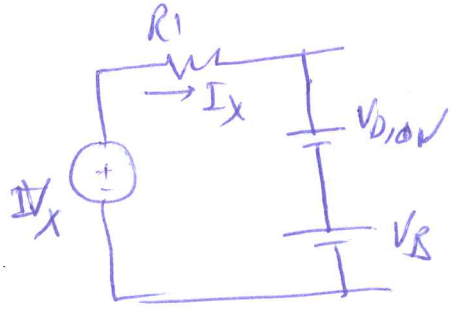


$-\infty < V_X < \infty$

Const.
D_1: voltage
~~Constant~~
mode

Draw $I_X = f(V_X)$

- assume D is ON
- Replacing D by its equivalent circuit $V_{D,ON}$
- Draw the circuit
- Write the diode current equation



$$V_X = I_X R_1 + (V_B + V_{D,ON})$$

$$I_X = I_{D1} = \frac{V_X - (V_B + V_{D,ON})}{R_1}$$

The transition level: (when $I_D = 0$).

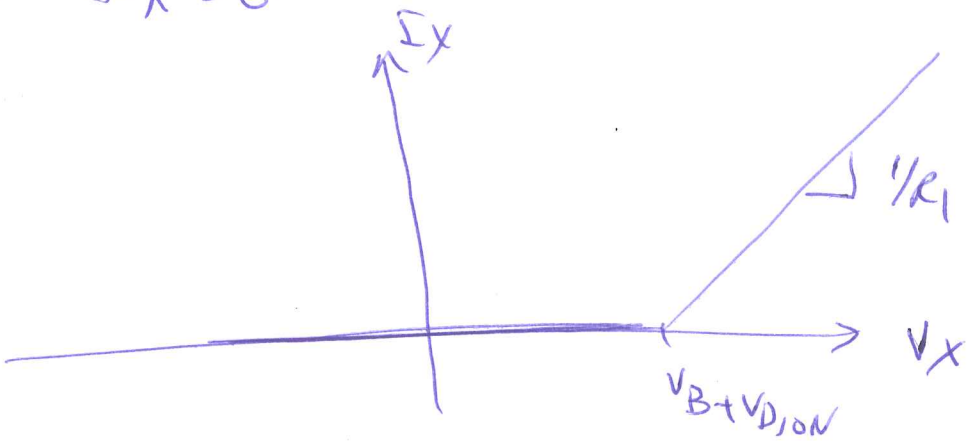
$$V_{Tran} = (V_B + V_{D1ON})$$

If $V_X \geq (V_B + V_{D1ON}) \Rightarrow$ D is ON

$$\Rightarrow I_X = \frac{V_X - (V_B + V_{D1ON})}{R_1}$$

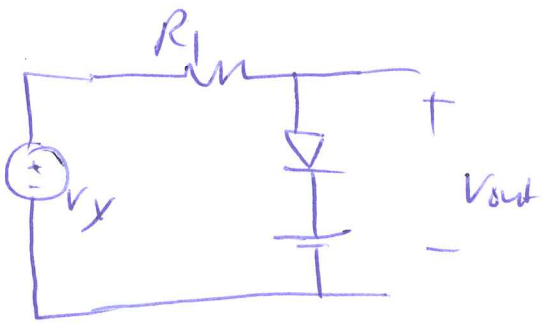
If $V_X < (V_B + V_{D1ON}) \Rightarrow$ D is OFF

$$\Rightarrow I_X = 0$$



b) Calculate

Plot $V_{out} = f(V_X)$

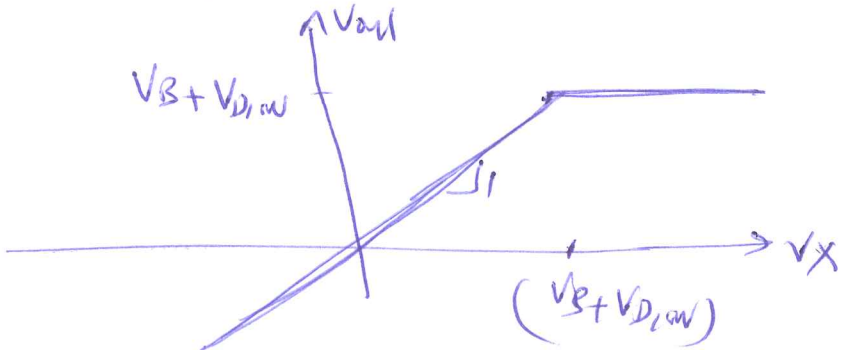


If $V_X \geq (V_{D1ON} + V_B)$

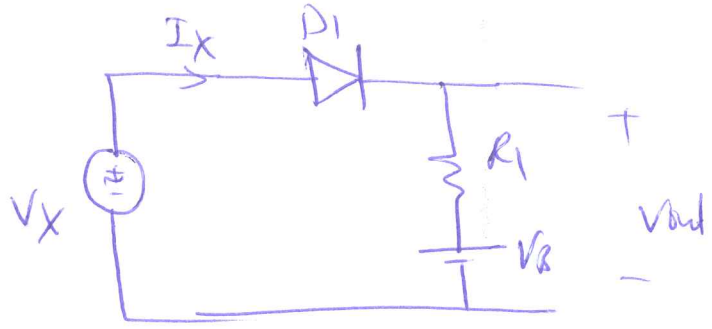
$\Rightarrow$ D is ON

$\Rightarrow V_{out} = V_{D1ON} + V_B$

If $V_X < (V_{D1ON} + V_B) \Rightarrow$ D is OFF $\Rightarrow V_{out} = V_X$



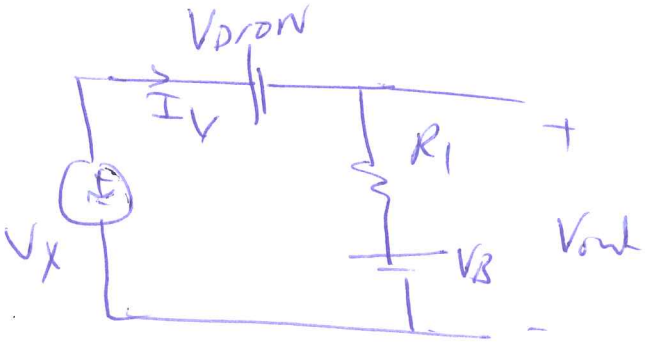
Example



Sketch $V_X = f(I_X)$

$V_{out} = f(V_X)$

- Assume D is ON
- Replacing D by $V_{D,ON}$
- Write I_D equation



$$I_X = I_D = \frac{V_X - (V_{D,ON} + V_B)}{R_1}$$

- find transition level

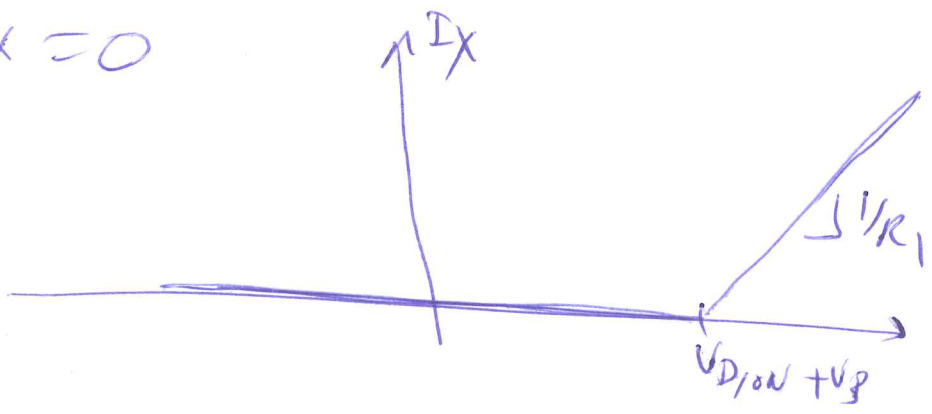
$$V_{Trans} = V_{D,ON} + V_{DB}$$

- If $V_X \geq (V_{D,ON} + V_B) \Rightarrow$ D is ON $\Rightarrow$

$$\Rightarrow I_X = \frac{V_X - (V_{D,ON} + V_B)}{R_1}$$

- If $V_X < (V_{D,ON} + V_B) \Rightarrow$ D is OFF

$$I_X = 0$$



To plot $V_{out} = f(V_X)$

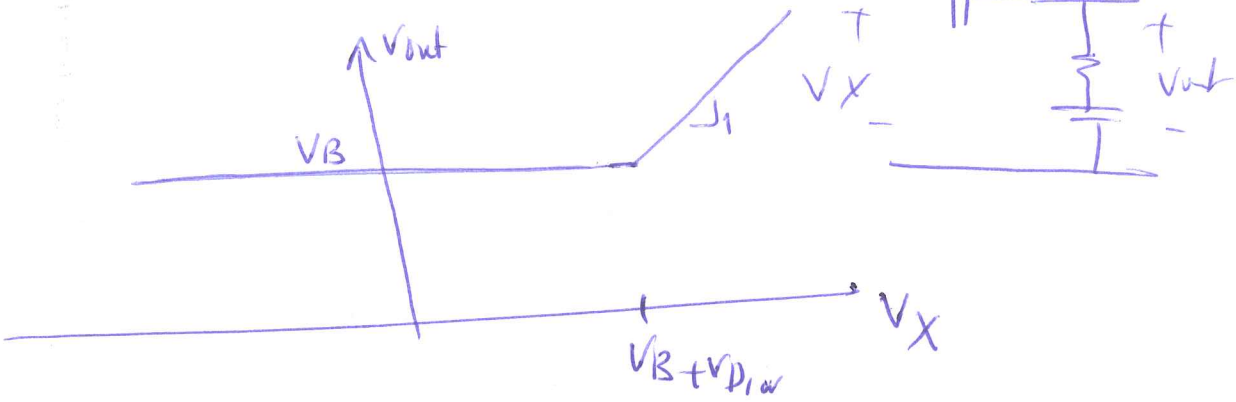
If $V_X < V_{tran} \Rightarrow$ D is OFF

$\Rightarrow V_{out} = V_{R_1} + V_B$

$= I_X R_1 + V_B = V_B$

If $V_X > V_{tran} \Rightarrow$ D is ON

$V_{out} = V_X - V_{D,ON}$



Today's lect

- Diode Circuit Examples
- Practical diode Circuits.

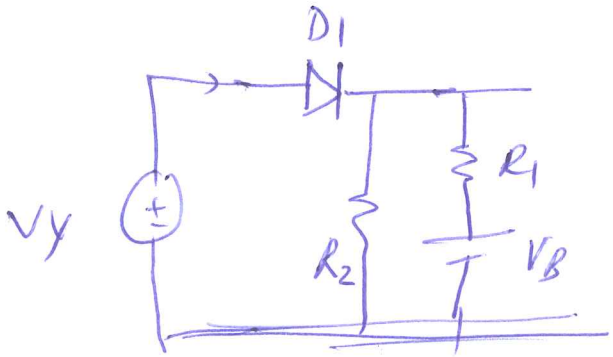
Review:

Procedure to solving the problem

- Begin with assumption for the state of each diode. The final result must be agree with these assumptions.
- If diode is about to turn ON or off its voltage = $V_{D,ON}$ and its current $I_D = 0$
- If the diode carries a current, the current must flow from anode to cathode.



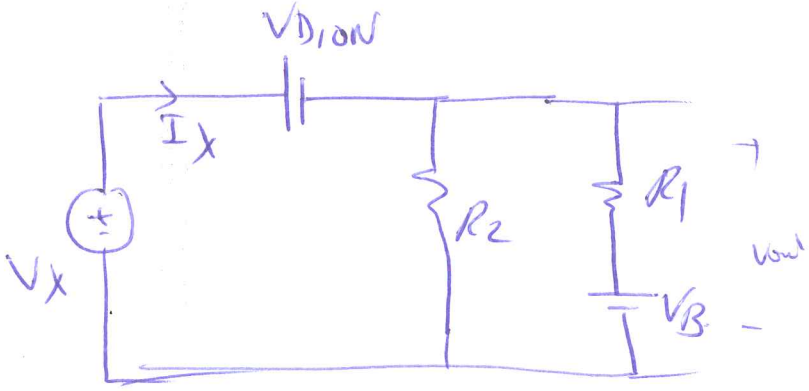
Example:



plot $I_X = f(V_X)$

$-\infty < V_X < \infty$

- assume D is ON
- Replacing D by $V_{D,ON}$



When D is ON

$$V_{out} = V_X - V_{D,ON} \quad , I_X > 0$$

When D is OFF $\Rightarrow I_X = 0$

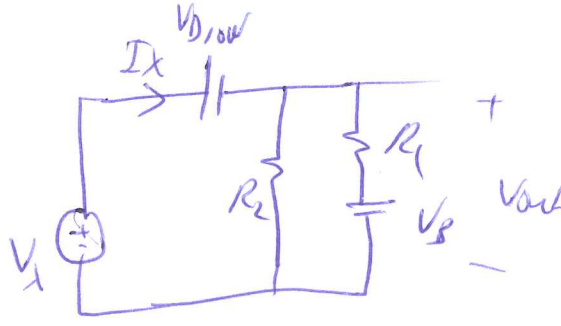
$$V_{out} = V_{R_2} = \frac{R_2}{R_1+R_2} V_B$$

That means, we have to find the value of V_X must be greater than V_{R_2} by $V_{D,ON}$ inorder the diode to be ON

$$V_{transition} = V_{D,ON} + V_{R_2} = V_{D,ON} + \frac{R_2}{R_2+R_1} V_B$$

So If $V_X > V_{D,ON} + V_{R_2} \Rightarrow$ D is ON

Using Electric circuit methods to find I_X



KVL $\quad V_X = V_{D,ON} + V_{out}$

KCL: $\quad I_X = I_{R_2} + I_{R_1}$

$$I_X = \frac{V_{out}}{R_2} + \frac{V_{out} - V_B}{R_1} \quad \rightarrow (1)$$

$$V_{out} = V_X - V_{D,ON} \quad \rightarrow (2)$$

from (1, 2)

$$I_X = \left(\frac{1}{R_2} + \frac{1}{R_1}\right)\left[V_X - V_{D,ON}\right] - \frac{V_B}{R_1}$$

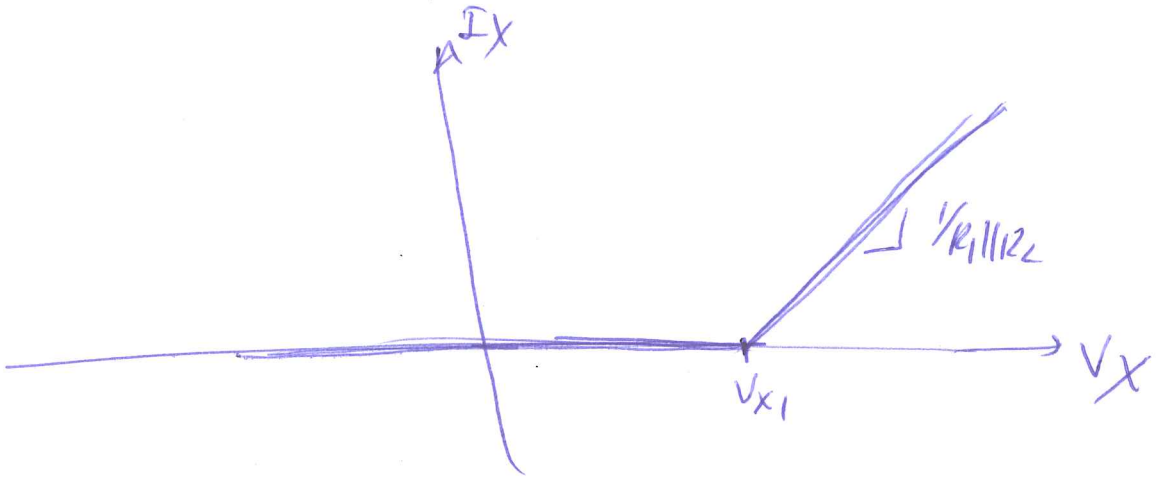
$$= \left(\frac{1}{R_1 \| R_2}\right)\left(V_X - V_{D,ON}\right) - \frac{V_B}{R_1}$$

when $I_X = 0$

$$\frac{V_X}{R_1 \| R_2} = \left(\frac{V_{D,ON}}{R_1 \| R_2} + \frac{V_B}{R_1}\right)$$

Transition level

$$\boxed{V_{X_1} = V_{D,ON} + \left(\frac{R_1 \| R_2}{R_1}\right) V_B}$$



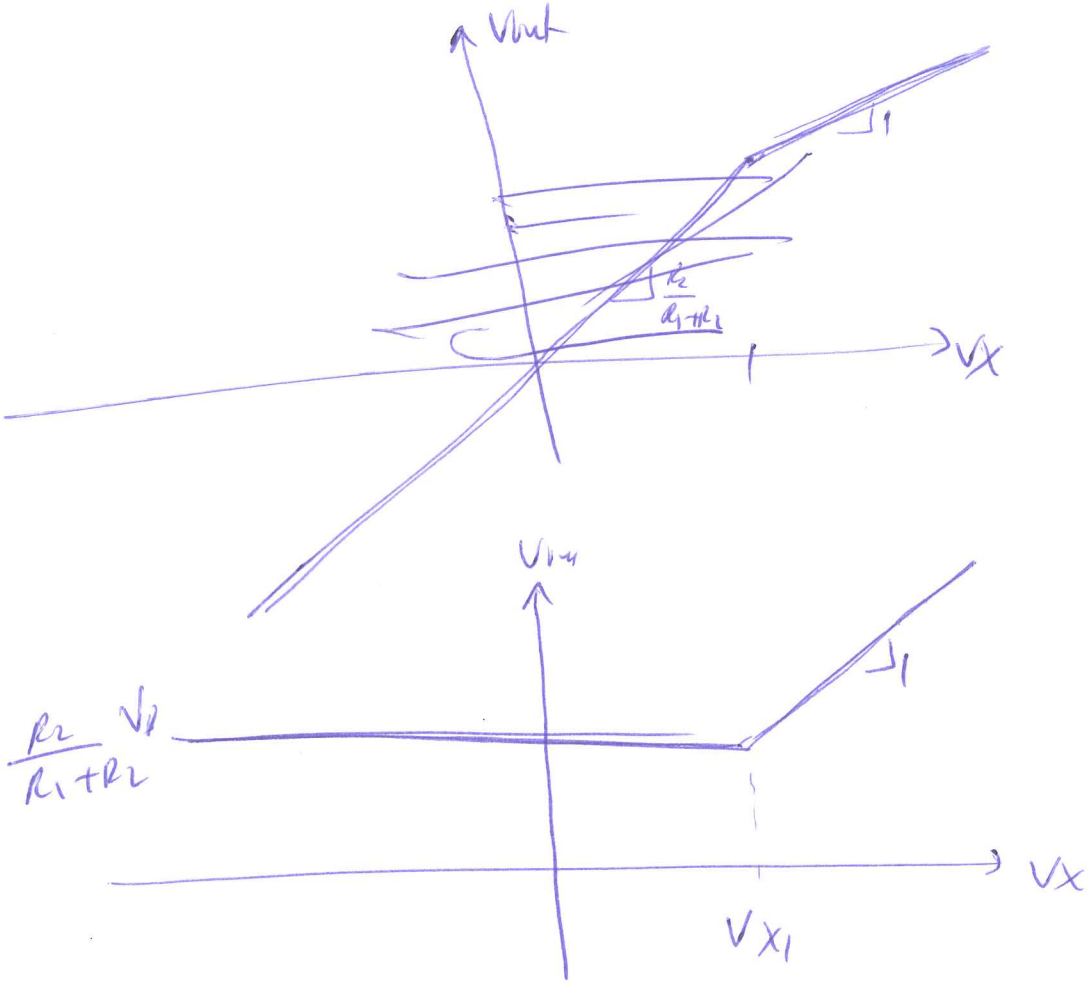
Quiz $V_{out} = f(V_X)$

If $V_X > V_{tran} \Rightarrow$ D is ON

$\Rightarrow V_{out} = V_X - V_{D,ON}$

If $V_X < V_{tran} \Rightarrow$ D is OFF

$$V_{out} = \frac{R_2}{R_1+R_2} V_B$$



$I_{R_1} = f(V_X)$

$I_{R_2} = f(V_X)$

Practical Diode Circuits :-

1) Rectifier :
2) Limitters (Clipper)
3) Voltage doublers
4) level shifts.

1] Rectifier :-

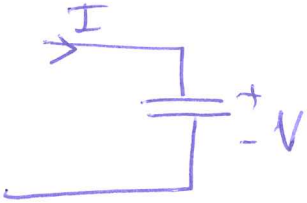
Basic Concepts :

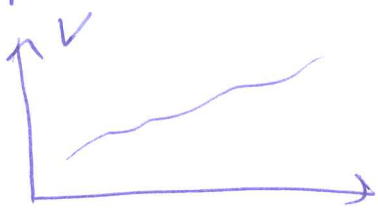
1) Analyze Circuit to obtain I-V Characteristics or input/output characteristics.
2) Also can analyze by studying the time Response
3) Concepts of tracking, example

$$V_{in} = V_x - V_{D,ON}$$

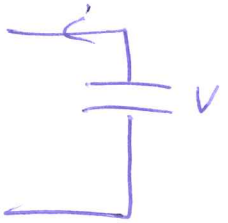
Thus means V_{in} tracks V_x peraphs with a constant diffenence.

4) Quick Review of Capacitors





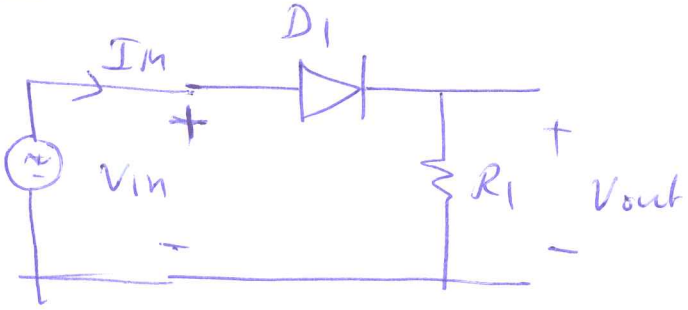
push more current ⇒ so the voltage increase



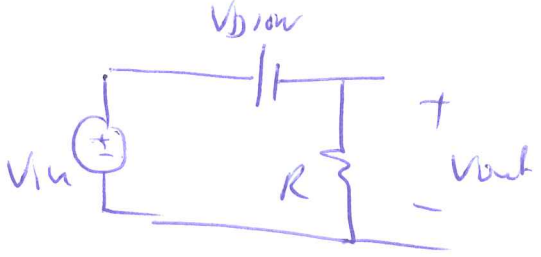
taking current from capacitor so the voltage decrease

Half wave Rectifiers

Assume constant voltage model



- assume D is ON
- Replacing D by $V_{D,ON}$



$$I_{in} = \frac{V_{in} - V_{D,ON}}{R}$$

- To find transition level $I_{in} = 0$.

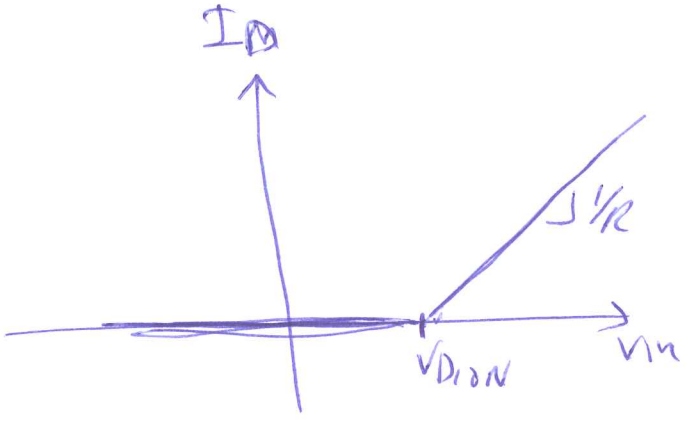
$$V_{in} = V_{D,ON}$$

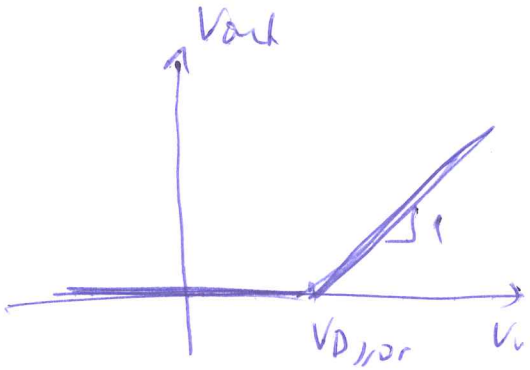
If $V_{in} > V_{D,ON} \Rightarrow D$ is ON $\Rightarrow I_{in} = \frac{V_{in} - V_{D,ON}}{R}$

$\Rightarrow V_{out} = V_{in} - V_{D,ON}$

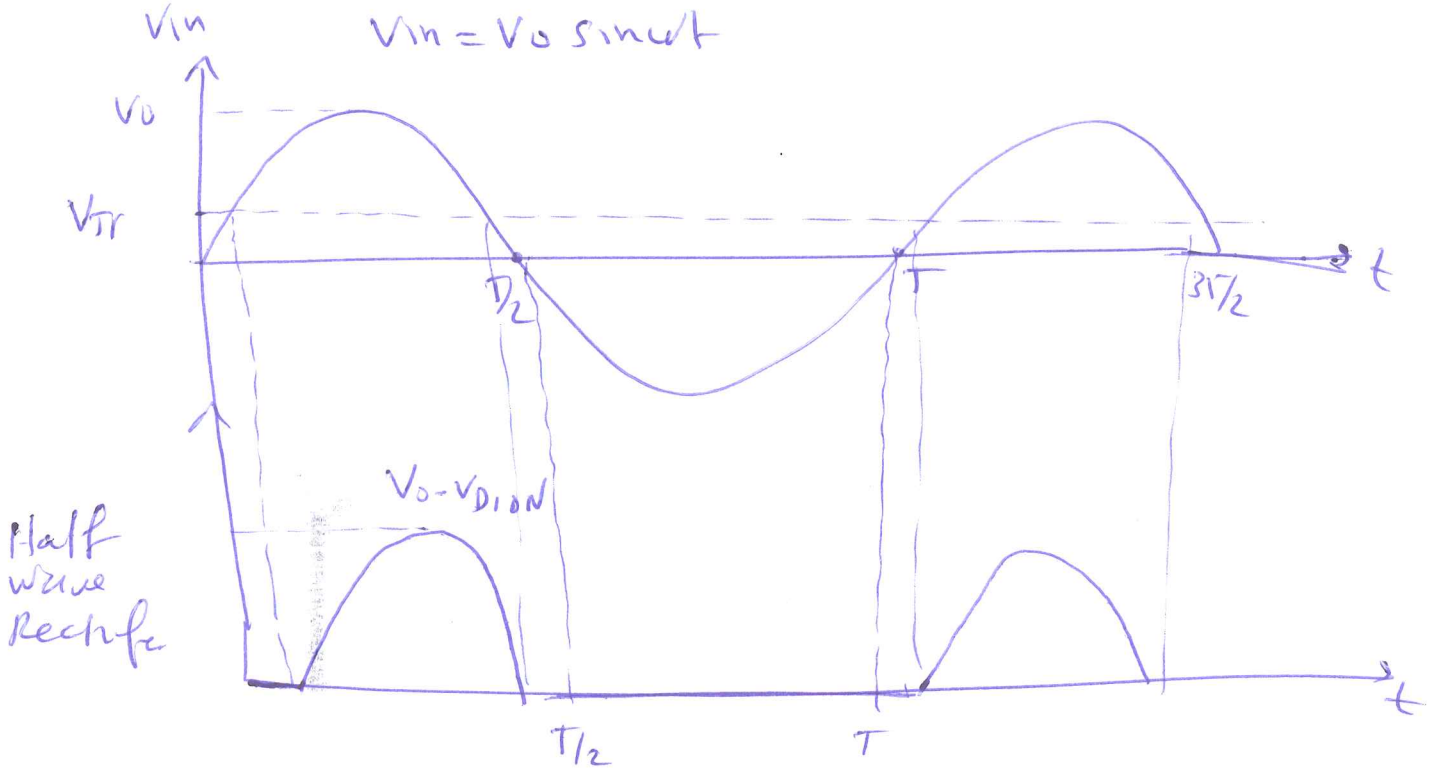
If $V_{in} < V_{D,ON} \Rightarrow D$ is OFF $\Rightarrow I_D = 0$.

$V_{out} = 0$.





Time Response:



Today's lecture

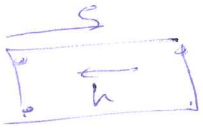
- pn junction
  - * Applications
  - * Basic Structure
  - * Behaviour in Equilibrium
  - * Behaviour in Reverse Bias.

Review:

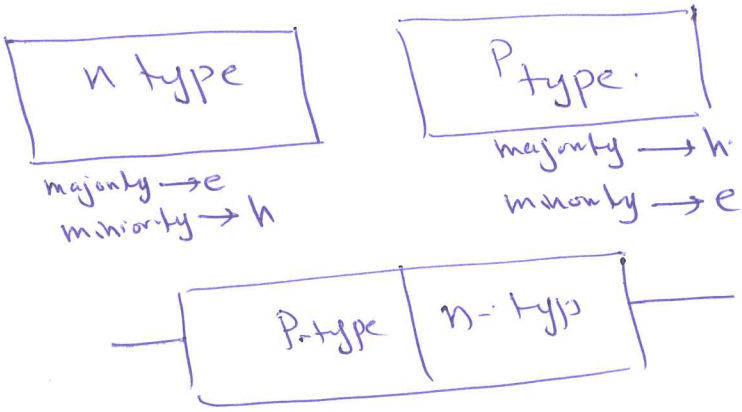
Current Conduction :-

* $J_{drift} = (\mu_n n + \mu_p p)\, q \mathcal{E}$

* $J_{diffusion} = \left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx}\right) q$



pn junction (diode).



pn junction called (diode)

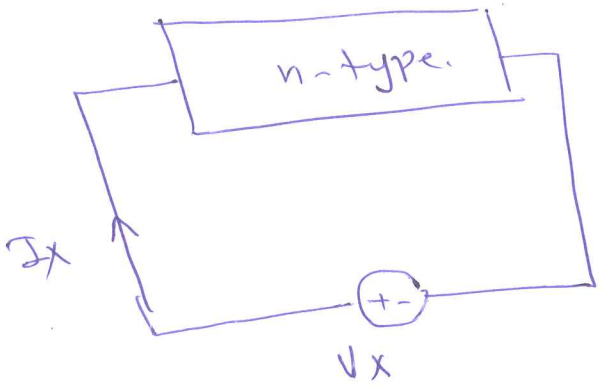


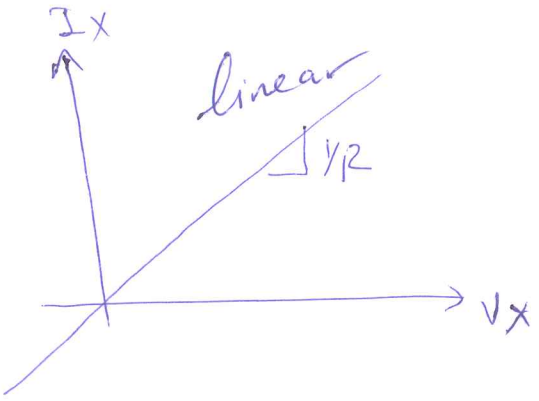
Application:

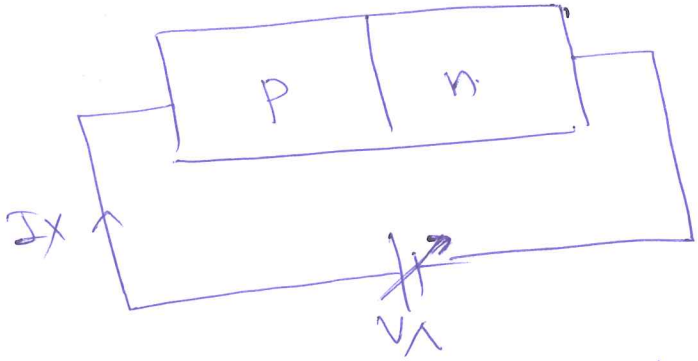
- Charger / Adapter
- Voltage multipliers.

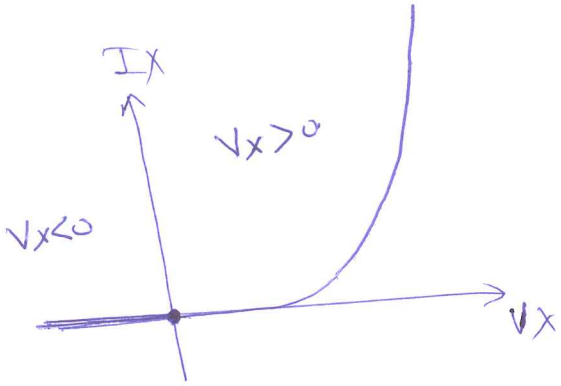
Quick Experiments :-

$V = IR$









⇒ Pn junction has non-linear function between V_x and I_x

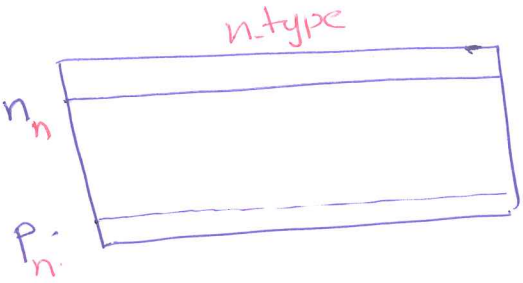
Two questions:

1) How do the charge carrier redistribute themself after pn junction is formed

2) How does the Pn junction behave under three Conditions:
   - No Bias (Equilbrium state)
   - Reverse Bias
   - forward Bias

Some observations :

1) n type semiconductor



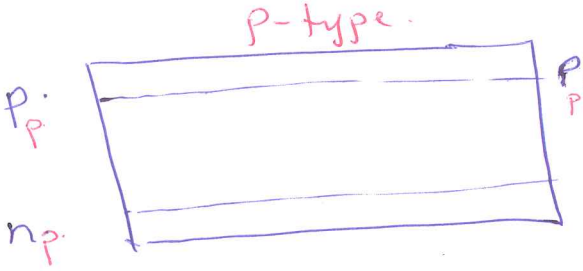
maj → n (e)

min → h

$n_n = N_D$

$p_n = \frac{n_i^2}{N_D}$

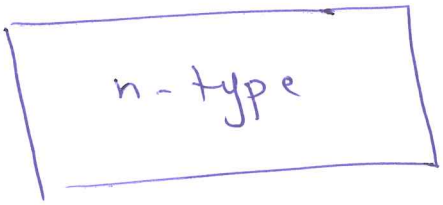
2) p-type



$p_p = N_a$

$n_p = \frac{n_i^2}{N_a}$

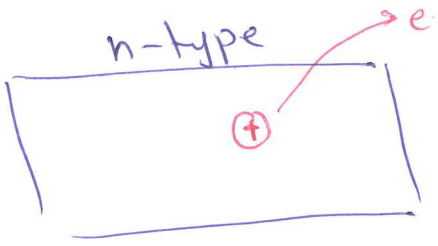
3)



what is the net charge of this device

⇒ Charge neutality

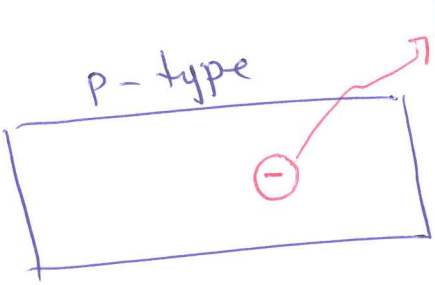
4)



If we take 1 electron out of the device

⇒ a positive ion is Created.

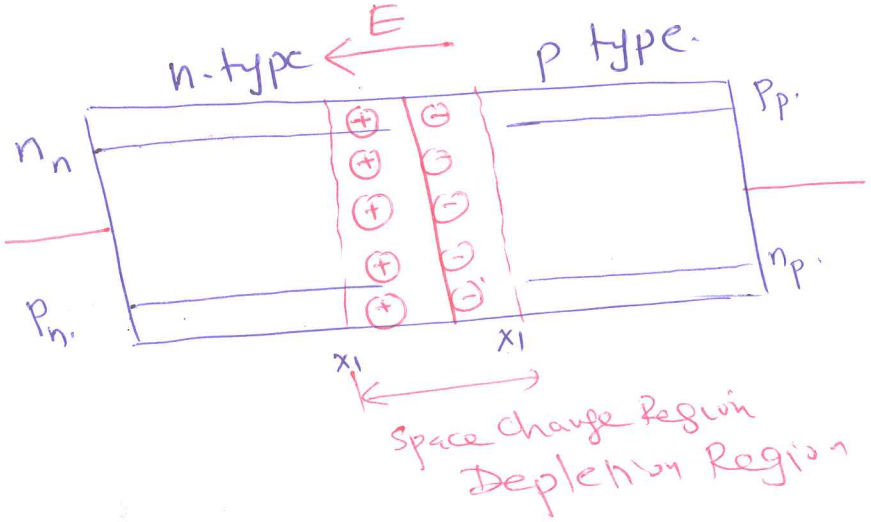
5)



If we take 1 hole out of the device

⇒ a negative ion is formed.

Pn junction (Diode)



- No electric fiued is applied (No Bias)
  ⇒ Equilibrium Condition'
- Diffusion current of electron = drift current of electron
  Diffusion current of holes = drift current of holes.

for hole:

$$D_p \frac{dP}{dx} q = \mu_p P \mathcal{E} q$$

$$D_p \frac{dP}{P} = \mu_p \mathcal{E}\, dx$$

$$D_p \int_{P_n}^{P_p} \frac{dP}{d} = \mu_p \int_{x_1}^{x_2} \mathcal{E}\, dx$$

Remark:

$$\boxed{-\int_a^b \mathcal{E}\, dx = V(a) - V(b)}$$

$$D_p \ln \frac{P_p}{P_n} = \mu_p \underbrace{(V(x_1) - V(x_2))}_{V_0}$$

$$D_p \ln \frac{P_p}{P_n} = \mu_p V_o$$

$$V_o = \frac{D_p}{\mu_p} \ln \frac{P_p}{P_n}$$

$P_p = N_a$

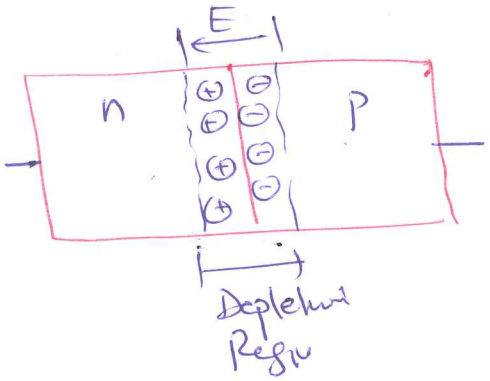
$P_n = \frac{n_i^2}{N_D}$

$$\boxed{V_o = \frac{D_p}{\mu_p} \ln \frac{N_a N_D}{n_i^2}}$$

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

$\frac{KT}{q} = 26mV$ @ $T = 300K^\circ$

V_o: built in potential.



Quit:

Is there any electric field outside the depletion Region?

⇒ No electric field

⇒ voltage drop = 0

⇒ neutral Region

⇒ I = 0.

Observations:

1) Same expression of V_o is obtained if the electron currents are considered.

2) If N_a and N_d in the order of $10^{16}/cm^3$ find V_o

$$V_o = 26mV \ln \frac{N_a N_d}{n_i^2}$$

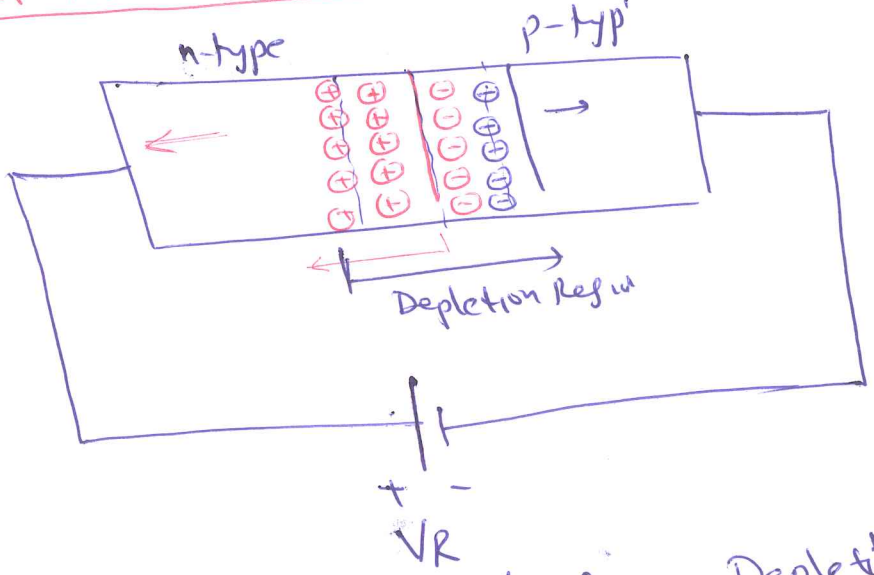
$$= 26mV \ln \frac{10^{32}}{10^{20}} = 720\,mV$$

Typical values of V_o are in the rage of (700 mV – 800 mV)

3) V_o is localized.

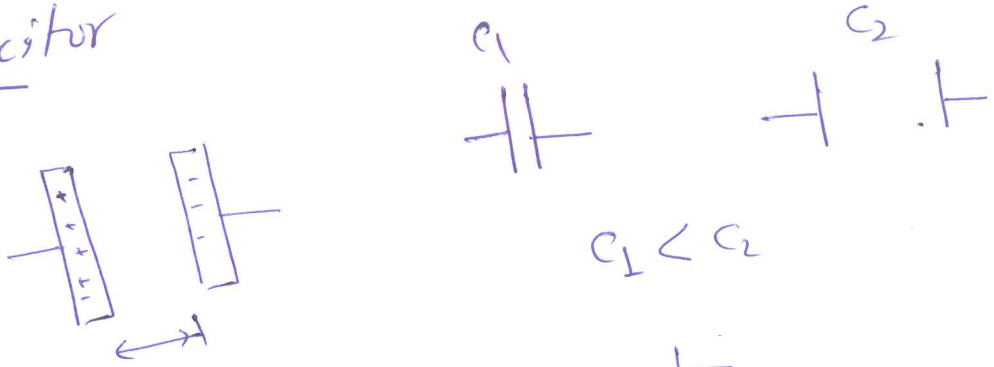
4) We can't measure V_o from outside.

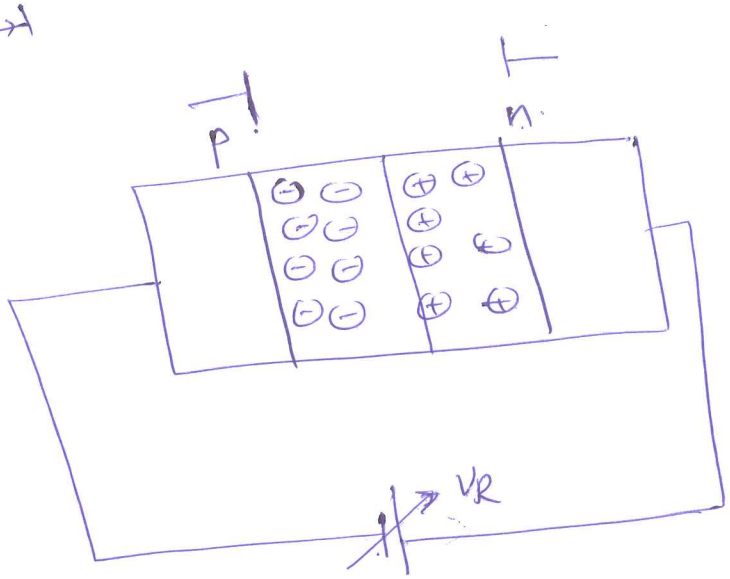
2) PN junction in Reverse Bias:



If we apply reverse voltage ⇒ Depletion Region becomes wide.

Capacitor



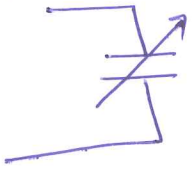


$Z_C = \frac{1}{j\omega C}$

When we apply reverse voltage the the value Capacitance decrease => because the of cap two plate, becomes more far them befor

=) the capacitance value can be controlled by the voltage => vanable capacitor

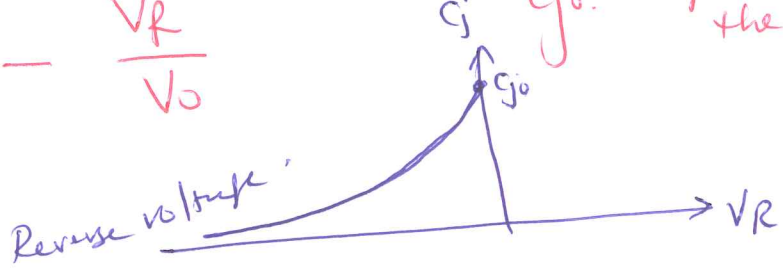
Varactor



$$C_j = \frac{C_{j0}}{\sqrt{1 - \frac{V_R}{V_0}}}$$

C_j: Capacitance of the junction

C_{j0}: Capacitance under the equilbrium sta

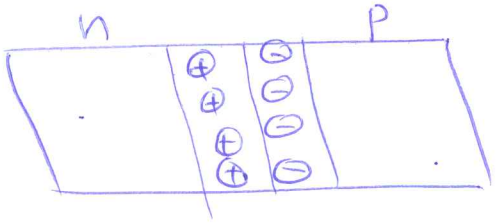


Today's lecture:-

- Pn junction in forward Bias
- Modeling the pn junction

Review:

- Pn junction in equilbrium (No bias)

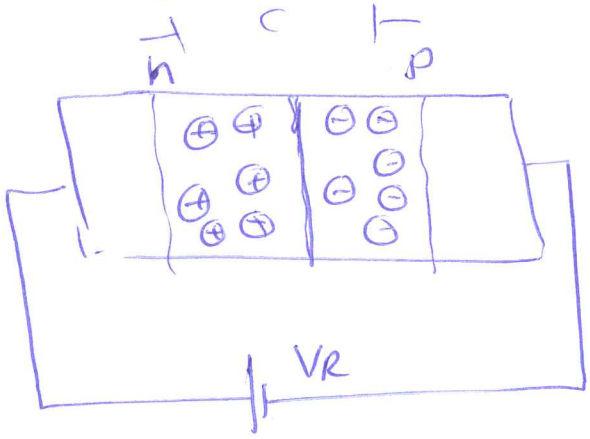


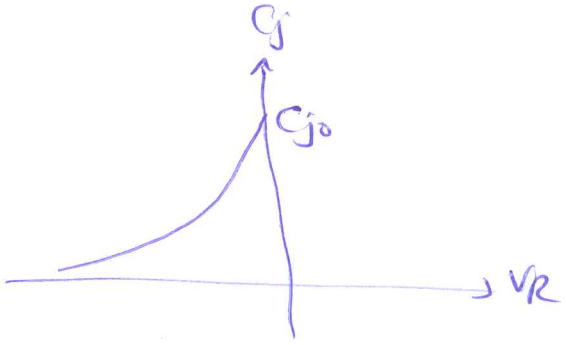
$$V_o = \frac{KT}{q} \ln \frac{N_a N_d}{n_i^2}$$

$\frac{KT}{q} = 26\,mV$

$V_o \cong (700 - 800\,mV)$

- Pn junction in Reverse Bias

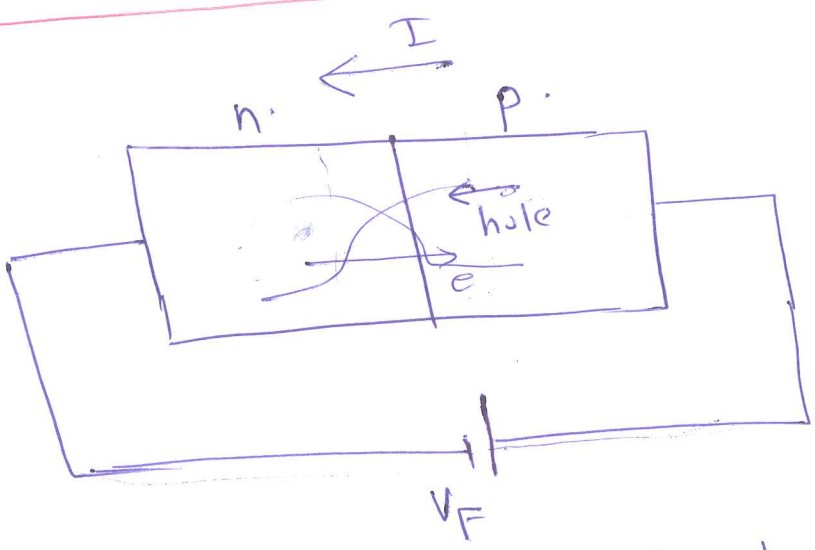




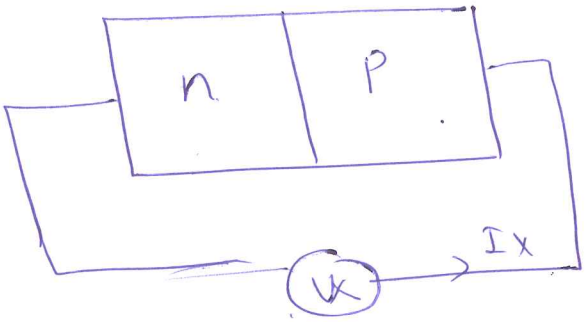
the value of varactor changes by changing the reverse voltage

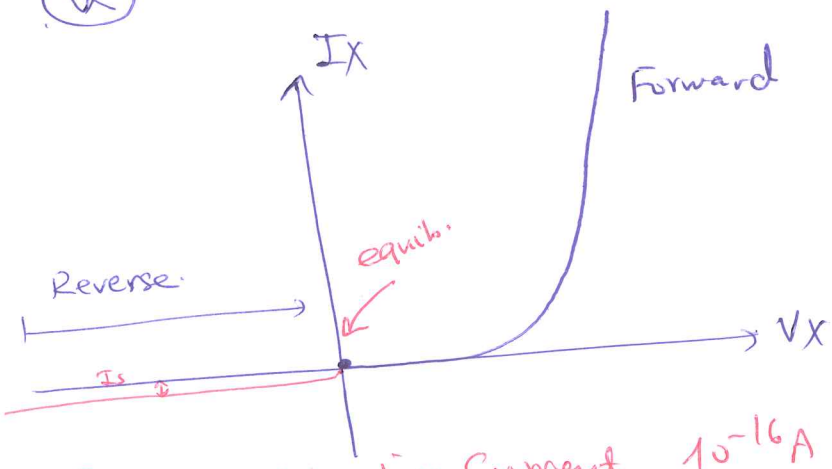
$$C_j = \frac{C_{jo}}{\sqrt{1 - \frac{V_R}{V_o}}}$$

pn junction in forward Bias:



- positive thermal will push the holes.
- negative thermal will push the electron



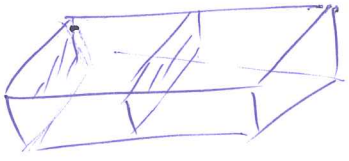


Is: reverse saturation Current 10^{-16} A

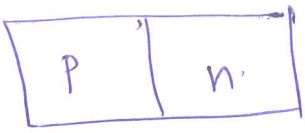
$$I_{junction} = I_S \exp\left(\frac{V_D}{V_T} - 1\right)$$

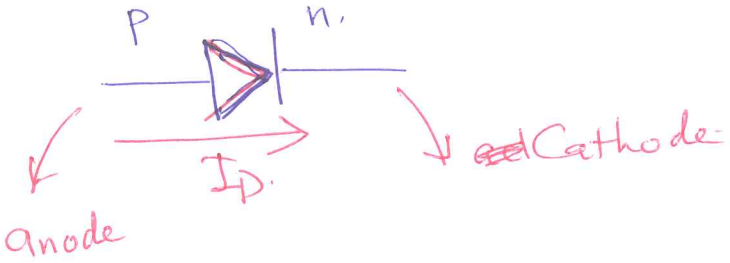
$$V_T = \frac{KT}{q} = 26\,mV$$

$$I_S = A q n_i^2 \left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p}\right)$$

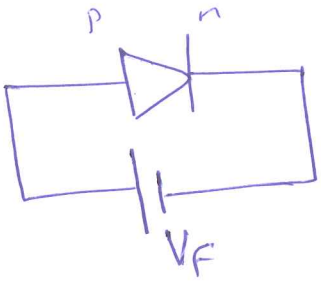


A: cross section
n_i intrinsic density
D_n, D_p : diversity of e/h
L : length

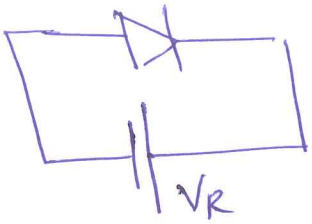




Forward Bias:



Reverse



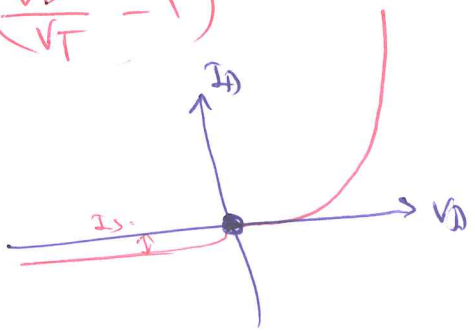
$$I_D = I_S \exp\left[\frac{V_D}{V_T} - 1\right]$$

when V_D more positive than V_T $(V_D > 4V_T)$ $(4 \times 26mV)$ $(V_D > 104mV)$

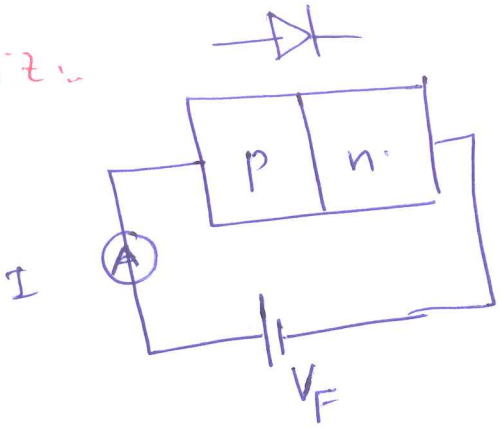
$$\Rightarrow \boxed{I_D = I_S \exp \frac{V_D}{V_T}} \Leftarrow \text{Forward Bias.}$$

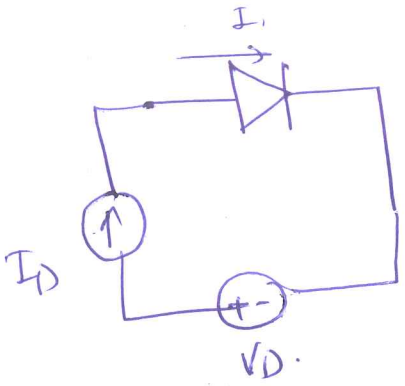
Study the equation $I_D = I_S \exp\left(\frac{V_D}{V_T} - 1\right)$

- No Bias: $\Rightarrow$ $I_D = 0$.
- Reverse Bias $(V_D < 0)$ $I_D = -I_S$.
- forward $\Rightarrow$ $I_D = I_S \exp \frac{V_D}{V_T}$



Quiz:





Determine the value of V_D (voltage across the diode if the current is I_1

$$I_D = I_S \exp\left(\frac{V_D}{V_T}\right)$$

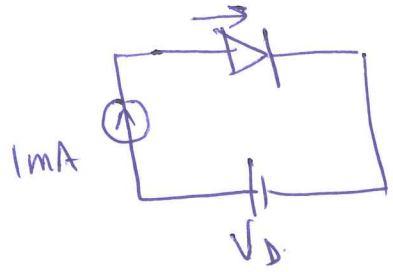
$$I_1 = I_S \exp \frac{V_D}{V_T}$$

$$\frac{I_1}{I_S} = \exp \frac{V_D}{V_T}$$

$$\ln \frac{I_1}{I_S} = \frac{V_D}{V_T}$$

$$\Rightarrow \boxed{V_D = V_T \ln \frac{I_1}{I_S}}$$

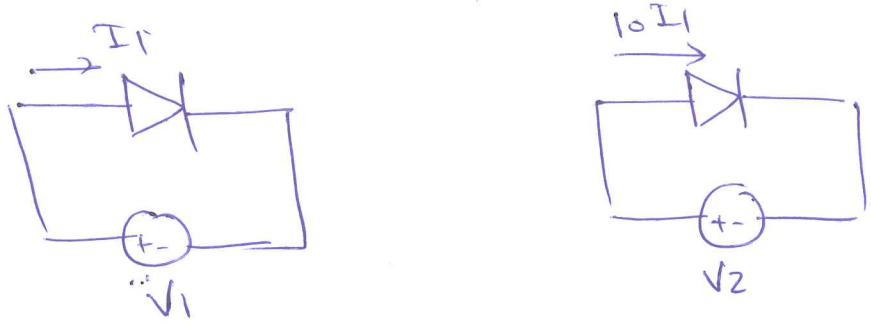
Example: $I_S = 10^{-16} A$, and we measure the forward bias current of 1mA, what is the applied volt



$$V_D = 26mV \ln \frac{1mA}{10^{-16}A} \simeq 778 mV$$

Example.

How much should the voltage increase if the current increase by a factor of 10



$$V_1 = V_T \ln \frac{I_1}{I_S}, \quad V_2 = V_T \ln \frac{I_2}{I_S}$$

$$V_2 = V_T \ln \frac{10 I_1}{I_S}$$

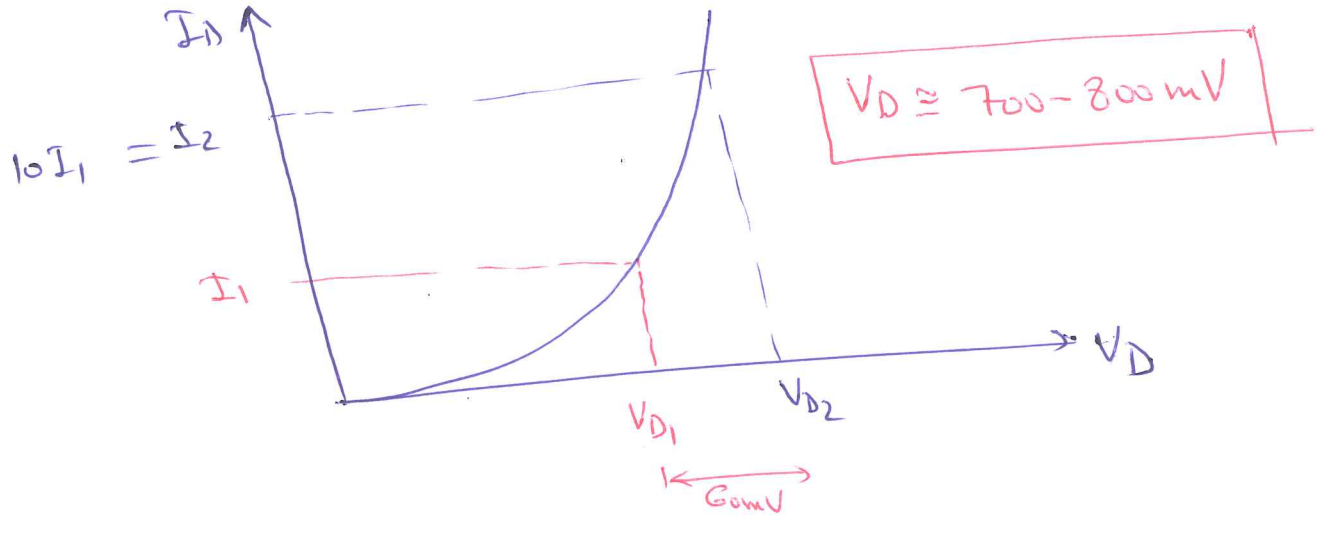
$$V_2 - V_1 = V_T \ln \frac{10 I_1}{I_S} - V_T \ln \frac{I_1}{I_S}$$

$$= V_T \ln \frac{10 I_1}{I_1} = V_T \ln 10$$

$$= 26\,mV \ln 10$$

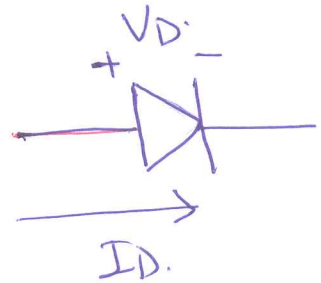
$$\simeq 60\,mV$$

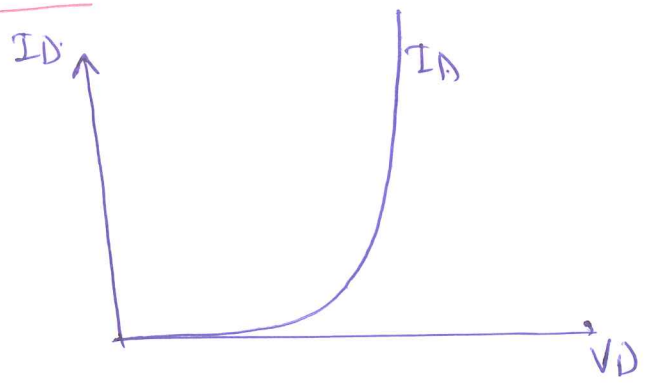
To increase the current by a factor of 10 the voltage must by increase by 60mV



$V_D \simeq 700 - 800\,mV$

Modeling of pn junction :

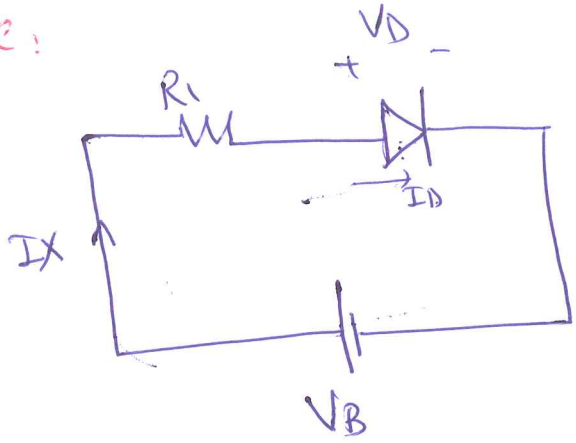




exponensional Model

$$I_D = I_S \exp\left(\frac{V_D}{V_T}\right)$$

Example :



Find I_X ?

- look to the battery to show if the diode is forward or Reverse.

$$V_D = V_T \ln \frac{I_X}{I_S}$$

- Assume D is ON.
- Apply KVL :

$$-V_B + I_X R_1 + V_D = 0$$

$$-V_B + I_X R_1 + V_T \ln \frac{I_X}{I_S} = 0$$

$$V_B = I_X R_1 + V_T \ln \frac{I_X}{I_S}$$

- Check : If $I_X > 0 \Rightarrow$ D is ON ✓

$I_X < 0 \Rightarrow$ D is OFF

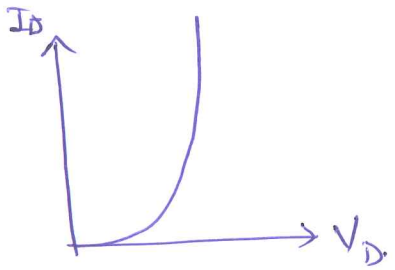
Today's lecture:-

- Diode Models
- Reverse Breakdown
- Circuit Example.

Review:

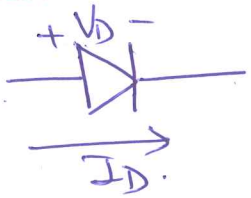
- pn junction in forward:-

$$I_D \simeq I_S \exp \frac{V_D}{V_T}$$



- Increasing I_D by a factor of 10 is done by increasing V_D by 60mV.

- Diode:-



$$I_D \simeq I_S \exp \frac{V_D}{V_T} \quad , \quad V_T = \frac{KT}{q} = 26mV$$

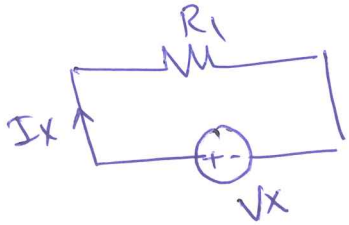
$$V_D = V_T \ln \frac{I_D}{I_S}$$

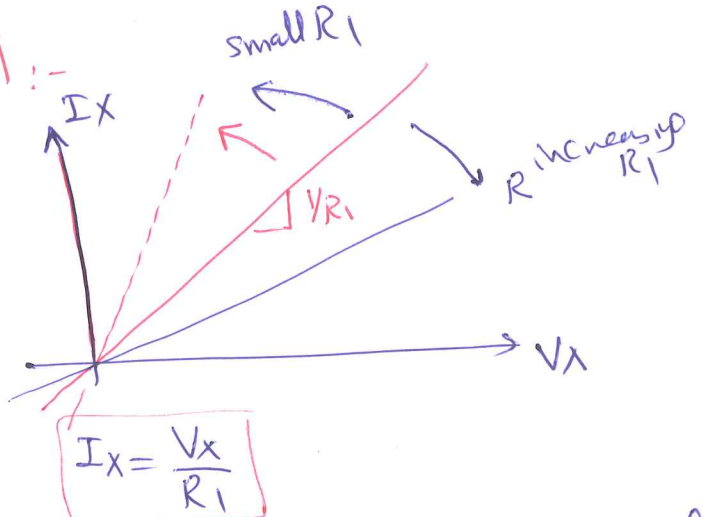
Diode Models.

* Constant voltage Model:-

- Observations

1)





$$I_X = \frac{V_X}{R_1}$$

If R_1 decrease
I_X increase

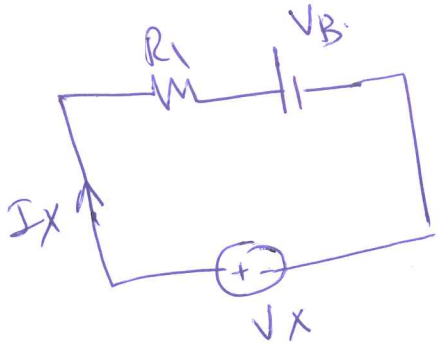
$R_1 \to 0$, $I_X \to \infty$
very large

If R_1 is increase $\Rightarrow I_X \Rightarrow$ become small

R_1 is very large $\Rightarrow$ I_X very small.

$R_1 \to \infty$ $\Rightarrow$ $I_X \to 0$.

2)



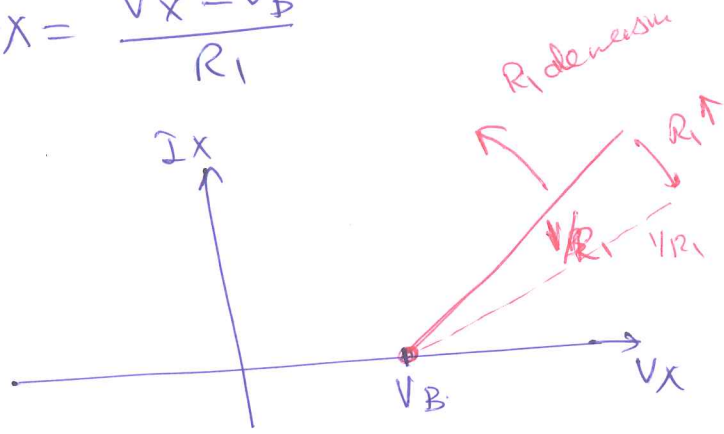
$I_X = f(V_X)$.

KVL $\quad V_X = I_X R_1 + V_B$.

$$I_X = \frac{V_X - V_B}{R_1}$$

when $V_X = V_B \Rightarrow I_X = 0$

when $V_X > V_B \Rightarrow I_X = \frac{V_X - V_B}{R_1}$



If R_1 increasing.

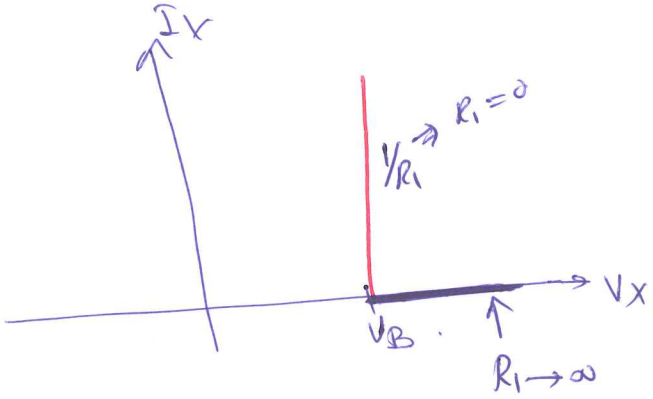
R_1 very large $\Rightarrow$ I_X very small.

$R_1 \longrightarrow \infty \quad \Rightarrow \quad I_X = 0$

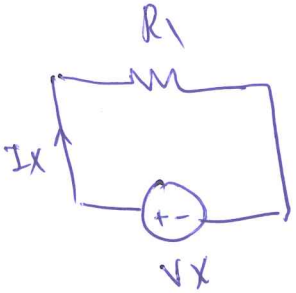
If R_1 decreasing

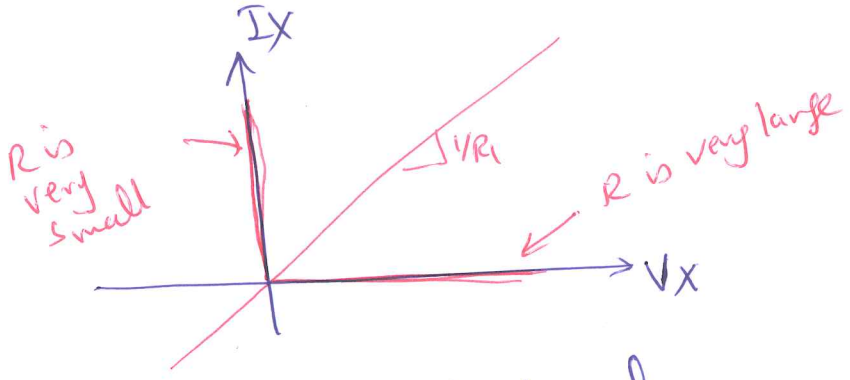
$I_X \uparrow$

If $R_1 \longrightarrow 0$, $I_X \uparrow \infty$



3)

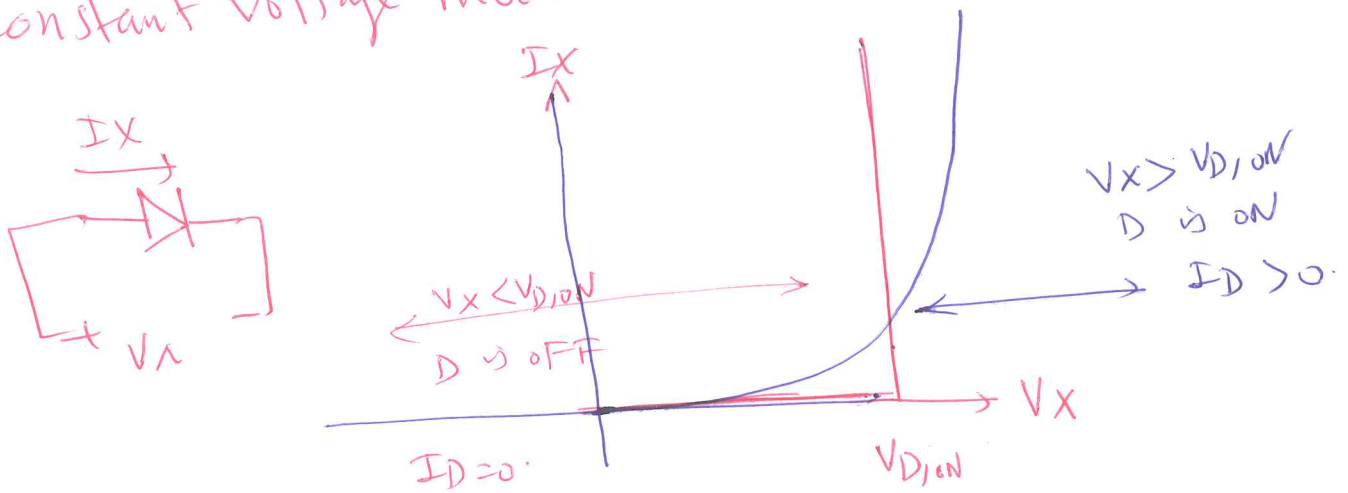


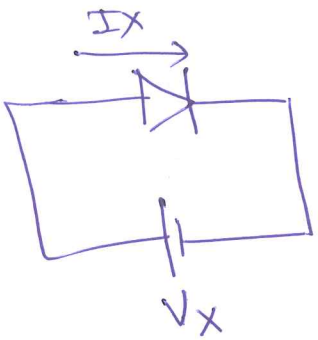


If $R_1 \uparrow \Rightarrow$ the slope becomes more horizonal.

If $R_1 \downarrow \Rightarrow$ the slope beame more vertical

Constant voltage model:-

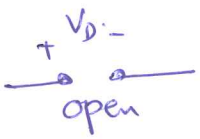


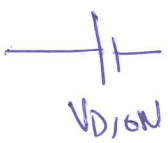
- 

using voltage constant model

1) If $V_X < V_{D,ON} \Rightarrow$ D is OFF $\Rightarrow$  $\Rightarrow I_D = 0$.

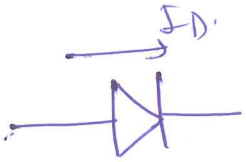
2) If $V_X > V_{D,ON} \Rightarrow$ D is ON $\Rightarrow$  $\Rightarrow I_D > 0$

Diode $\rightarrow$
- OFF $\Rightarrow$  $\Rightarrow I_D = 0$.

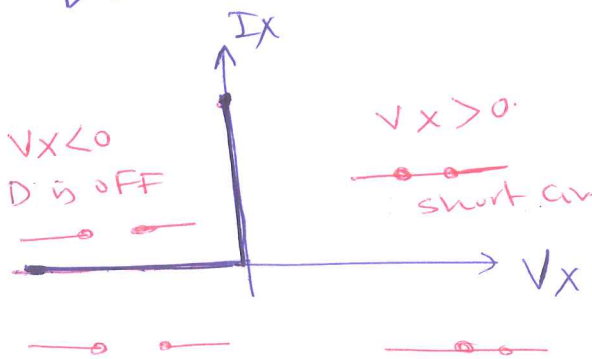
- ON $\Rightarrow$  $\Rightarrow I_D > 0$

In general $V_{D,ON} = (700 - 800\ mV)$

Ideal Diode Model

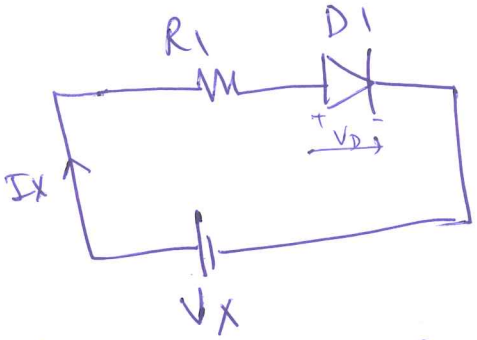


Ideal diode:- passes the positive voltage and blocks the negative voltage



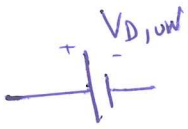
in ideal case -
$V_{D,ON} = 0$

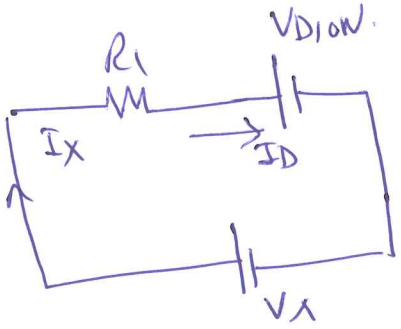
Example:



Using voltage constant model
Find IX ?

- D is forward Biasing
- assume D is ON
- Replacing D by its equivalent circuit



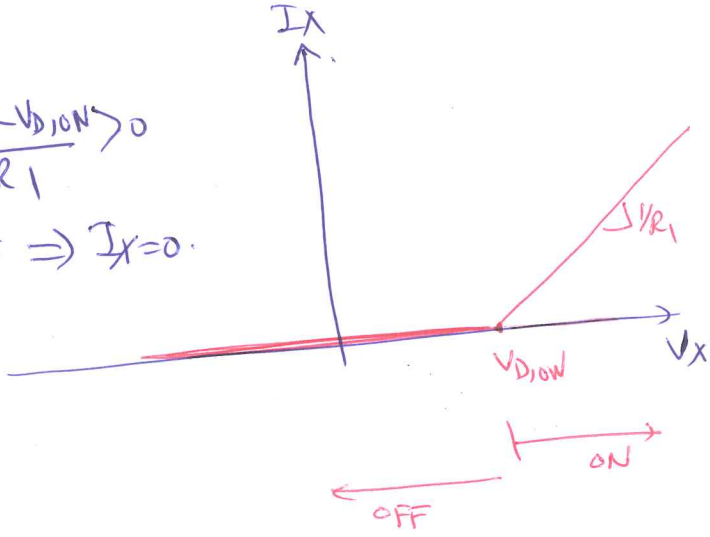


- Write KVL to find IX

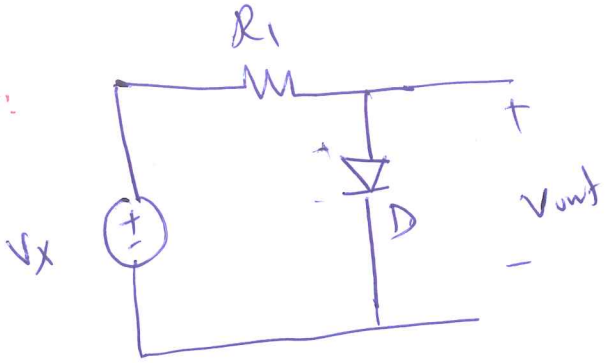
$V_X = I_X R_1 + V_{D,ON}$

$$I_X = \frac{V_X - V_{D,ON}}{R_1}$$

- If $V_X = V_{D,ON} \Rightarrow I_X = 0$
- If $V_X > V_{D,ON} \Rightarrow I_X = \frac{V_X - V_{D,ON}}{R_1} > 0$
- If $V_X < V_{D,ON} \Rightarrow$ D is OFF $\Rightarrow I_X = 0$



Example:



$-\infty < V_X < \infty$

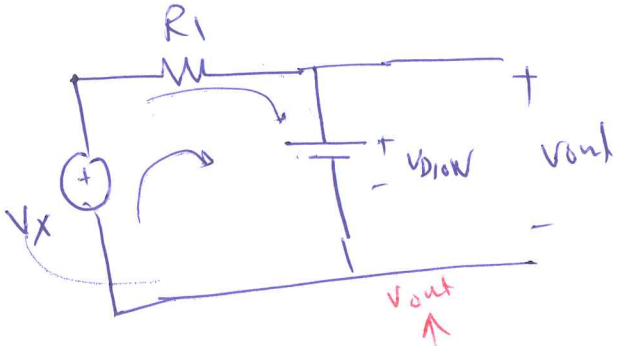
Plot $V_{out} = f(V_X)$

assume D is constant voltage model.

- Procedure to solve:
  - Test if diode is forward or Reverse
  - If diode is forward, assume it is ON
  - Replace the diode by its equivalent circuit
  - Write the equation of the diode current.
  - Assume $I_D = 0$ to find the transition level (V_{trans})
  - Check if $V_X > V_{trans} \Rightarrow$ ---
    if $V_X < V_{trans} \Rightarrow$ - —
  - Complete the solution.

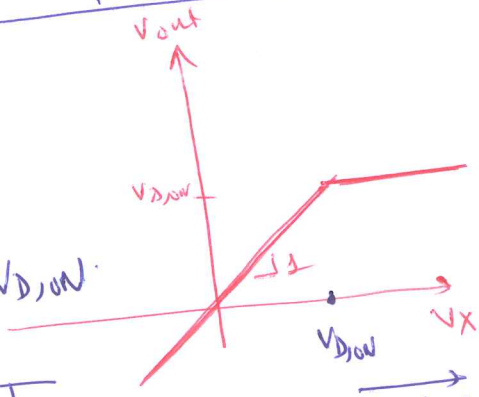
Solution: D is forward

- Assume D is ON



KVL: $-V_X + R_1 I_D + V_{D,ON} = 0$

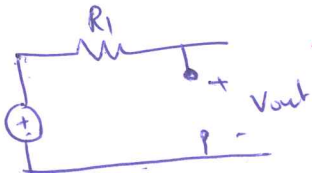
- $I_D = \dfrac{V_X - V_{D,ON}}{R_1}$
- $I_D = 0 \Rightarrow \boxed{V_{trans} = V_{D,ON}}$



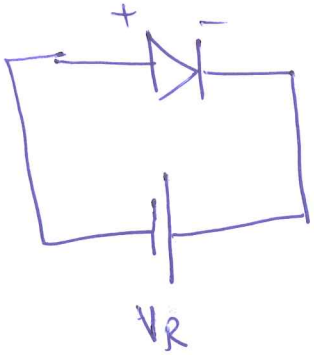
If $V_X \geq V_{D,ON} \Rightarrow$ D is ON $\Rightarrow V_{out} = V_{D,ON}$

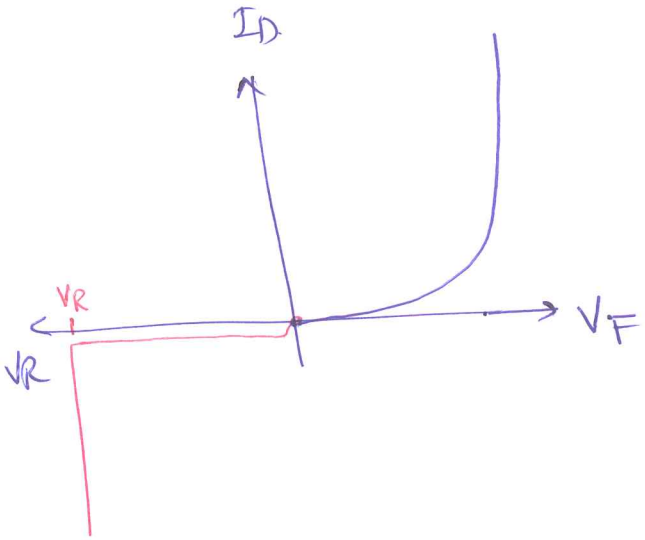
If $V_X < V_{D,ON} \Rightarrow$ D is OFF $\Rightarrow$

$\Rightarrow I_D = 0 \Rightarrow \boxed{V_{out} = V_X}$



Reverse Breakdown:





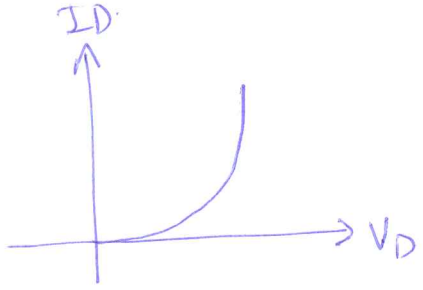
Today's lecture:-

- Summery of diode Models
- Practice with diode Circuits

Review:

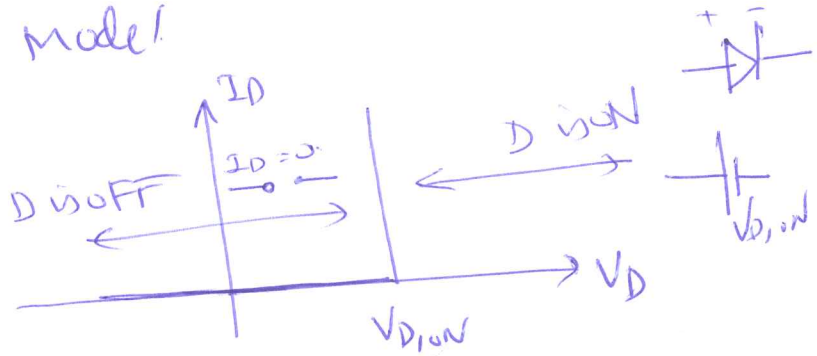
diode Model:

1) Exponential Model

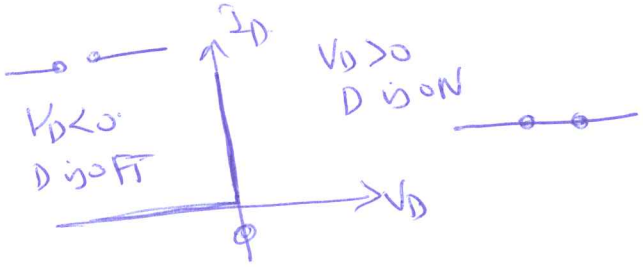


$$I_D = I_S \exp \frac{V_D}{V_T} \qquad V_T = 26mV \text{ @ room Temp}$$

2) Constant voltage Model

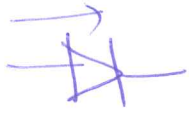


3) Ideal diode



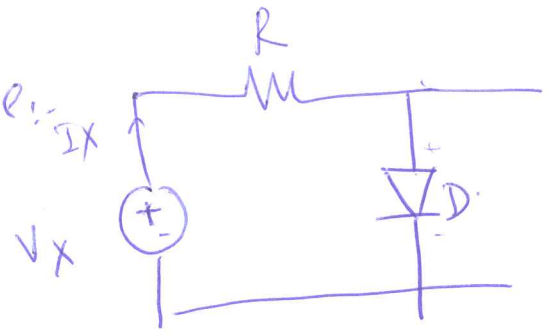
Diode Models:

1) All three models are non linear models
2) All three model distinguish between positive and negative voltage (Rectification)



3) Constant voltage model, passes the ⊕ voltage greater than $V_{D,ON}$ ($V_{D,ON} \cong 700 - 800mV$

Example:-

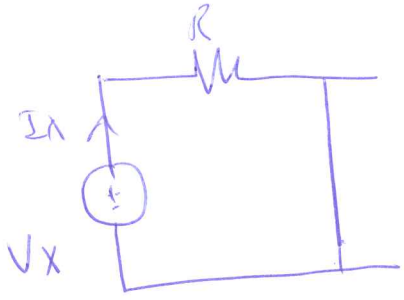


D is ideal Model

Plot $I_X = f(V_X)$

V_X changes from $(-\infty$ to $+\infty)$

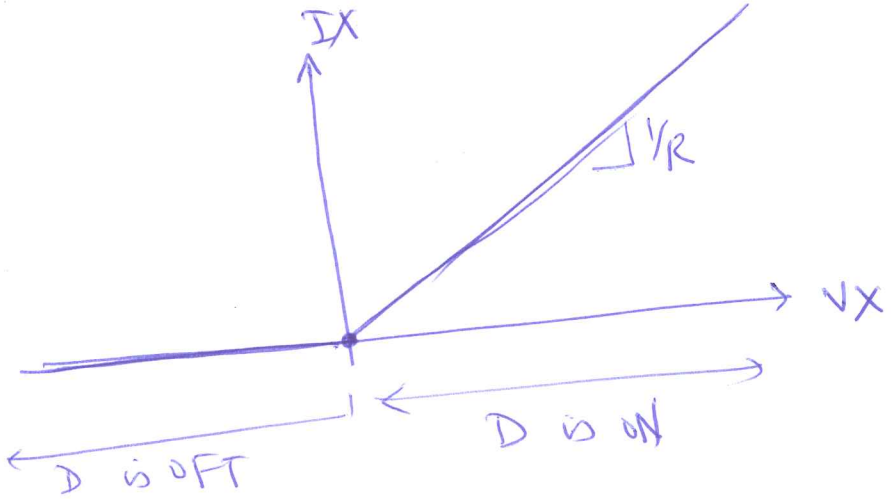
- Diode is forward.
- assume D is ON
- Replace D by its equivalent Circuit



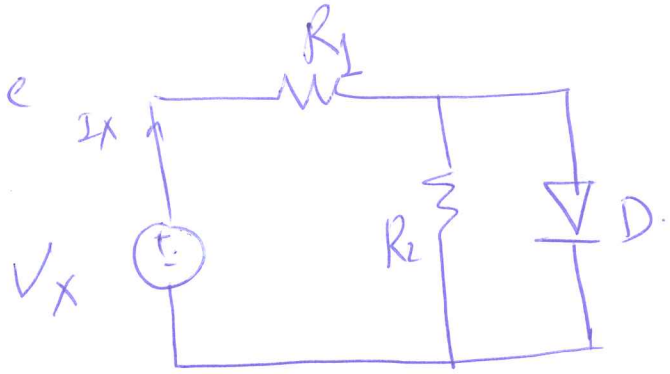
- $I_D = I_X = \frac{V_X}{R}$
- Transition level:- [the value of V_X, where $I_D = 0$]

$V_{transition} = 0$

- If $V_X \geq 0 \Rightarrow$ D is ON $\Rightarrow I_X = \frac{V_X}{R}$
- If $V_X < 0 \Rightarrow$ D is OFF $\Rightarrow I_X = 0$



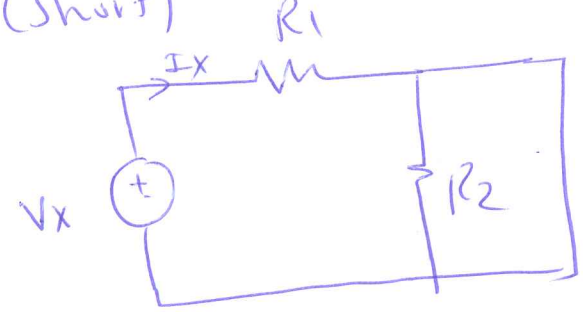
Example



D is ideal.

plot $I_X = f(V_X)$

- D is forward, D is ON
  - Replacing D by —o o— (short)

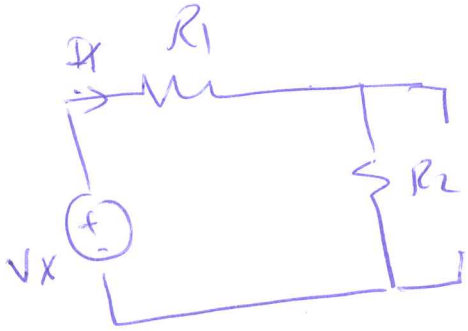


  - $I_X = \frac{V_X}{R_1}$

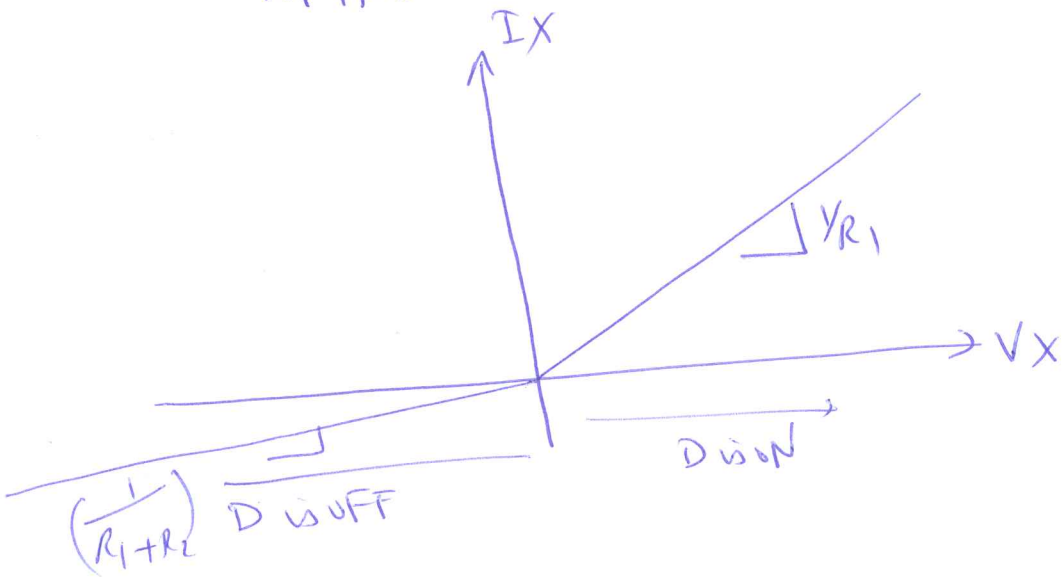
- If $V_X \geq 0$, D is ON

$\Rightarrow I_X = \frac{V_X}{R_1}$

- If $V_X < 0 \Rightarrow$ D is OFF $\Rightarrow$

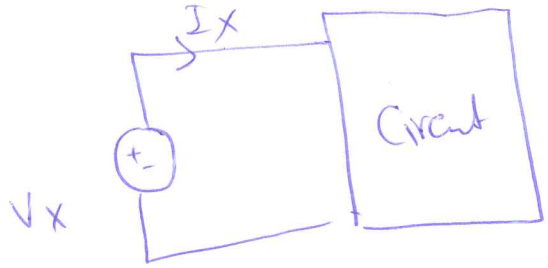


$I_X = \frac{V_X}{R_1 + R_2}$

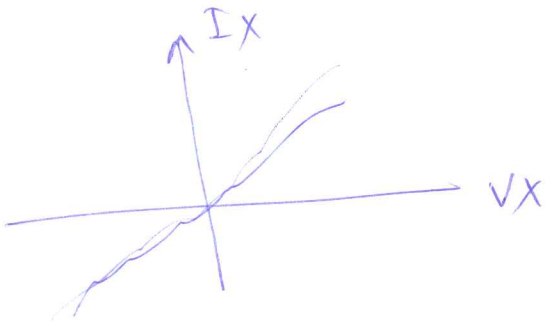


Types of characteristics

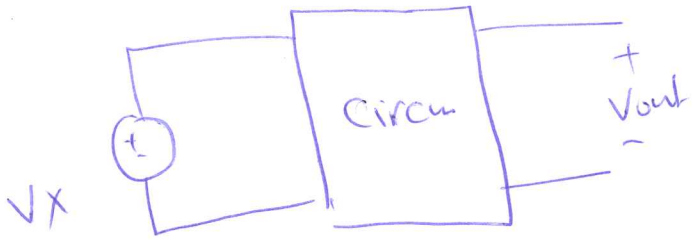
1) I-V characteristic



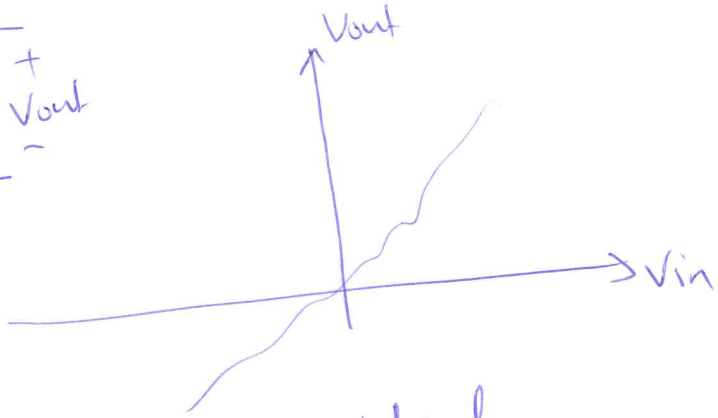
$I_X = f(V_X)$



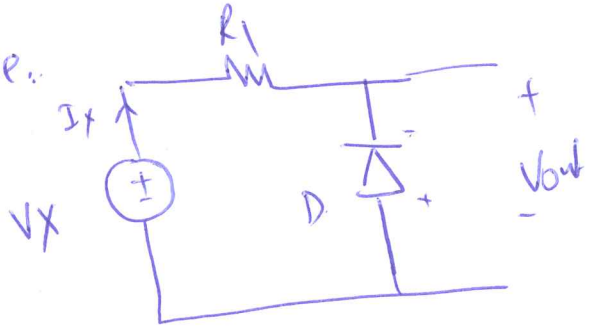
2) Input/output Charact.



$V_{out} = f(V_X)$



Example:

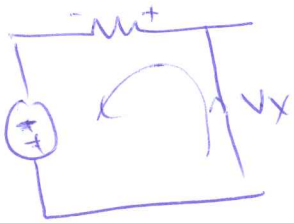


D is ideal

1) plot $I_X = f(V_X)$
2) plot $V_{out} = f(V_X)$

for negative V_X ⇒ D is forward. ⇒ D is on (assume.)

$$I_X = \frac{V_X}{R}$$

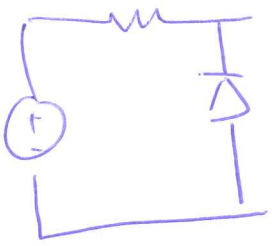


$$I_X = \frac{V_X}{R}$$

To find transition level:- $V_{trans} = 0$

- If $V_X > 0 \Rightarrow$ D is OFF

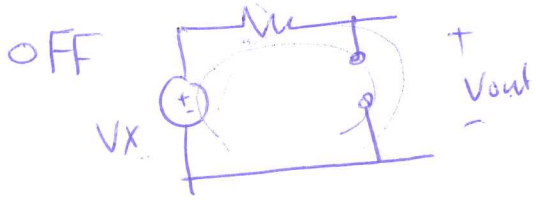
$\boxed{I_X = 0}$, $\boxed{V_{out} = V_X}$

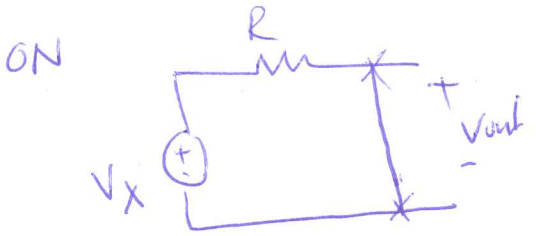


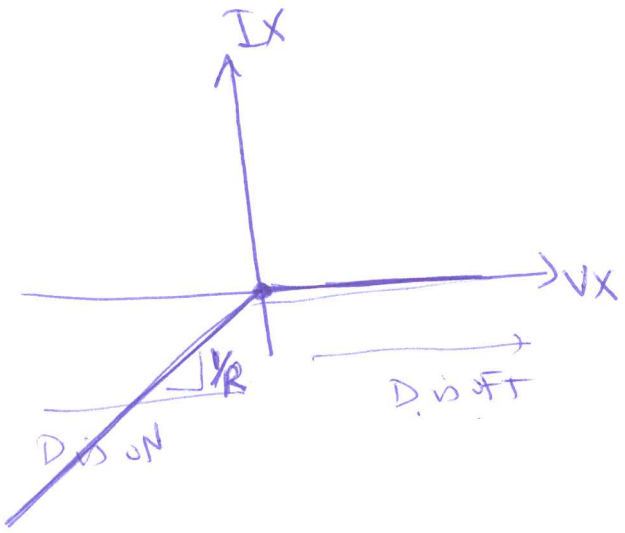
- If $V_X < 0 \Rightarrow$ D is ON

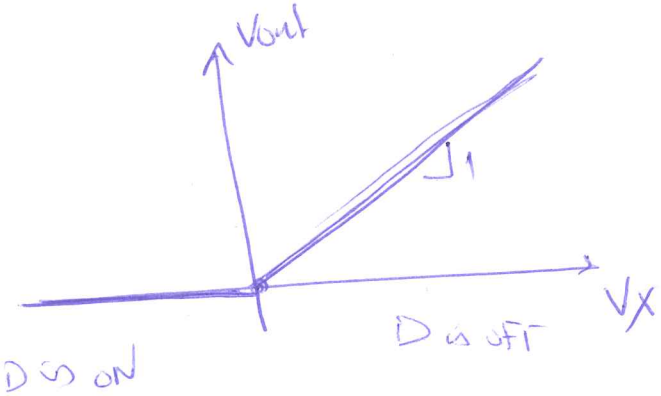
$$I_X = \frac{V_X}{R}$$

$$V_{out} = 0$$

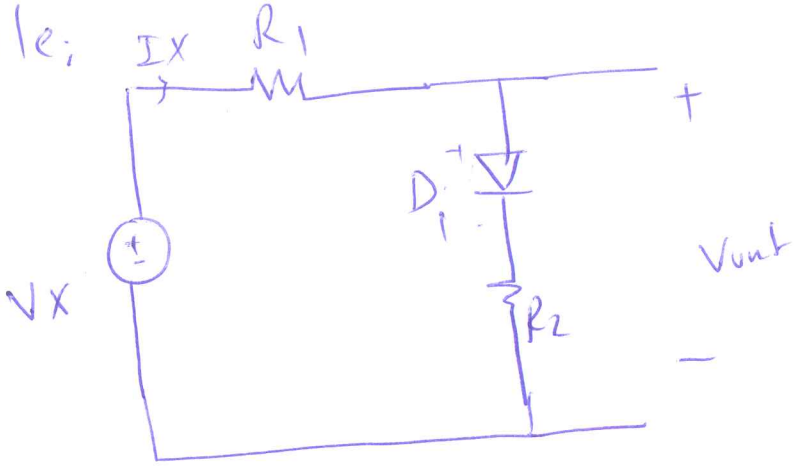








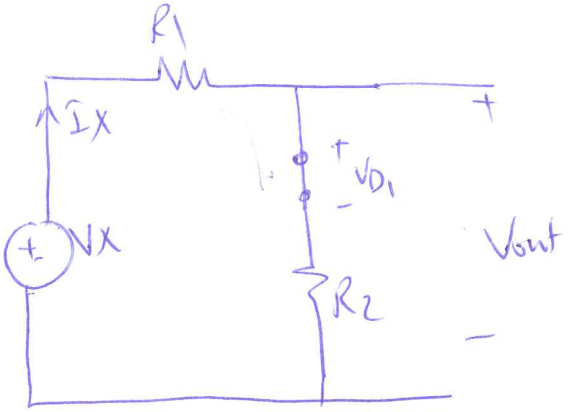
Example:



D is ideal

1) $I_X = f(V_X)$
2) $V_{out} = f(V_X)$
3) $V_{R_1} = f(V_X)$
4) $V_{D_1} = f(V_X)$
5) $V_{R_2} = f(V_X)$

- D is forward for positive value of V_X
- Assume D is ON



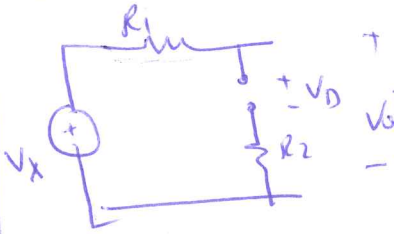
- $I_X = \frac{V_X}{R_1+R_2}$
- To find transition level:

when $I_X = 0 \Rightarrow V_X = 0 \Rightarrow$ **$V_{trans} = 0$**

- If $V_X \geq (V_{trans} = 0\,V) \Rightarrow$ D is ON

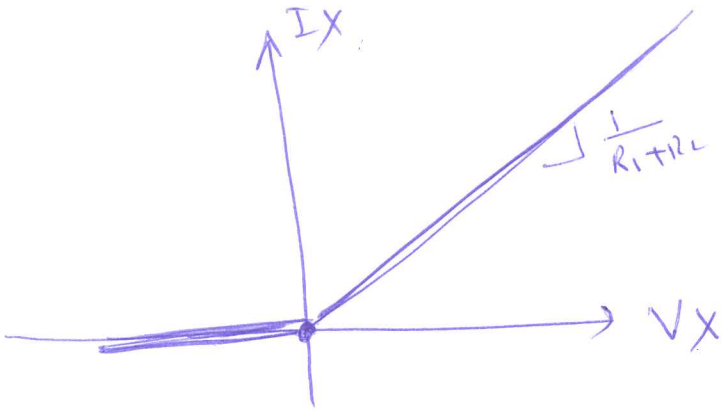
1) $I_X = \frac{V_X}{R_1+R_2}$
2) $V_{out} = \frac{R_2}{R_1+R_2} V_X$
3) $V_{R_1} = \frac{R_1}{R_1+R_2} V_X$
4) $V_{D_1} = 0$
5) $V_{R_2} = V_{out} = \frac{R_2}{R_1+R_2}$

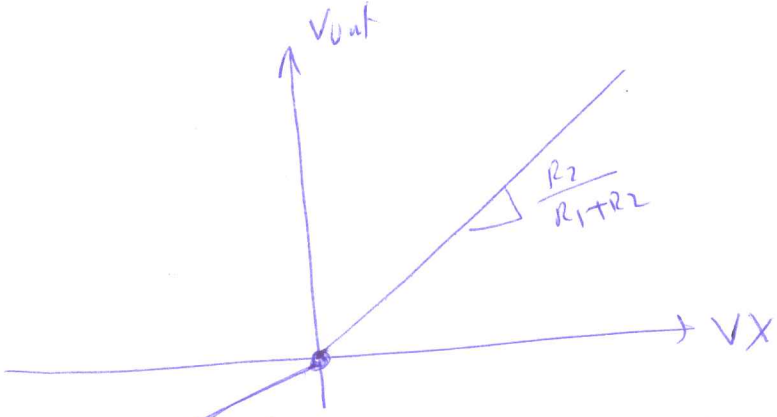
If $V_X < 0$
$\Rightarrow$ D is OFF

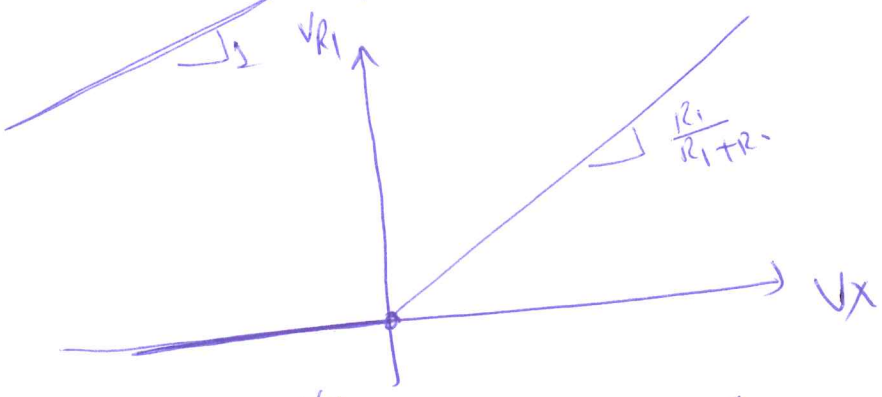


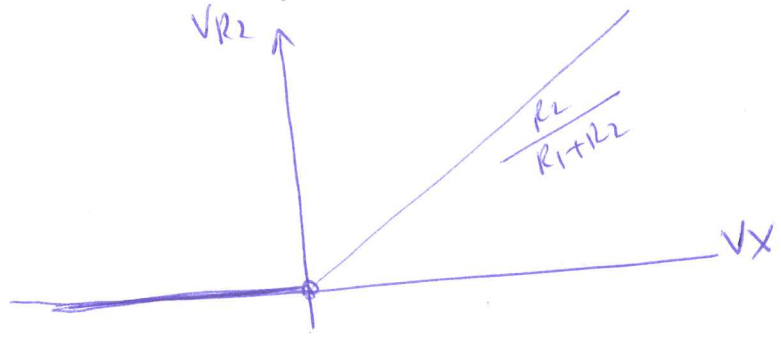
1) $I_X = 0$
2) $V_{out} = V_X$
3) $V_{R_1} = 0$
4) $V_{R_2} = 0$
5) $-V_X + V_{R_1} + V_{D_1} + V_{R_2} = 0$

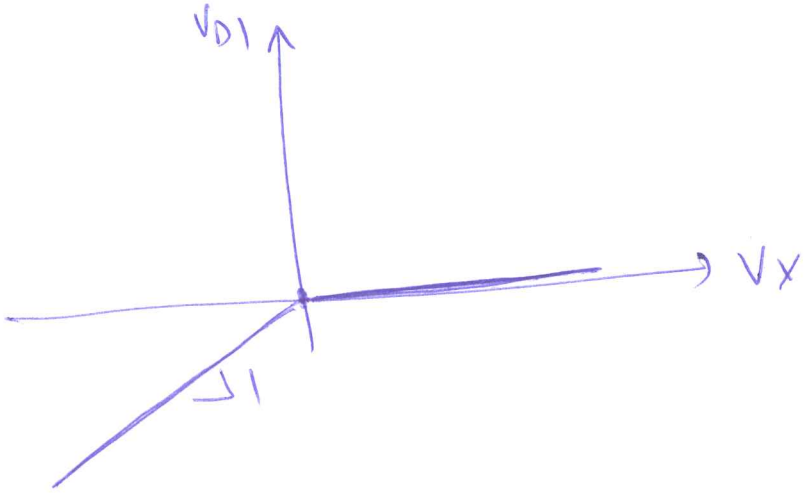
$V_{D_1} = V_X$


IX
$\frac{1}{R_1+R_2}$
VX


Vout
$\frac{R_2}{R_1+R_2}$
VX


1
VR1
$\frac{R_1}{R_1+R_2}$
VX


VR2
$\frac{R_2}{R_1+R_2}$
VX


VD1
VX
1

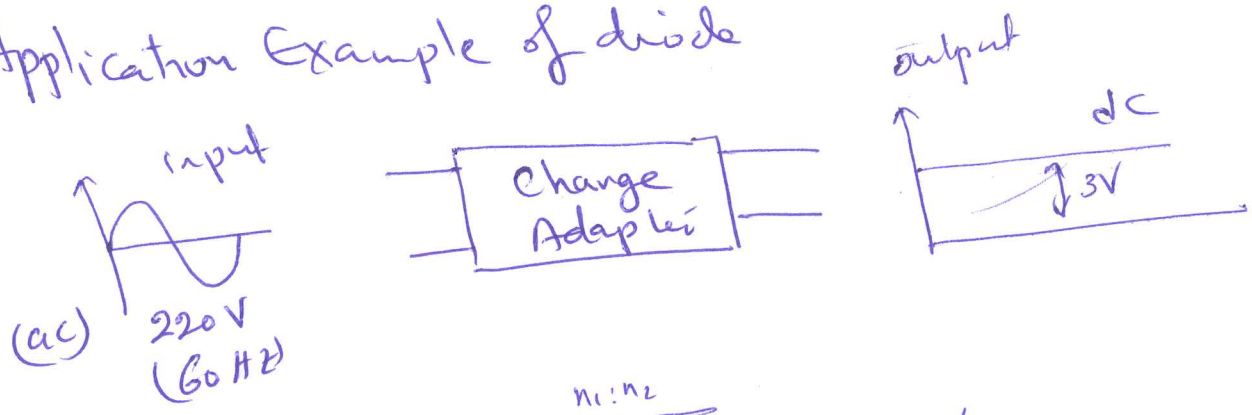
Today's lecture:-

- Application Example (Charger/Adapter)
- Principle of Diode Analysis
- Examples using voltage constant model.

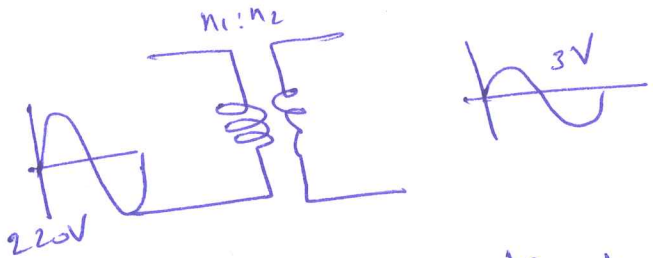
Review:-

- Three diode Models:-
  - * Exponential Model
  - * Voltage Constant Model
  - * Ideal model.

* Application Example of diode



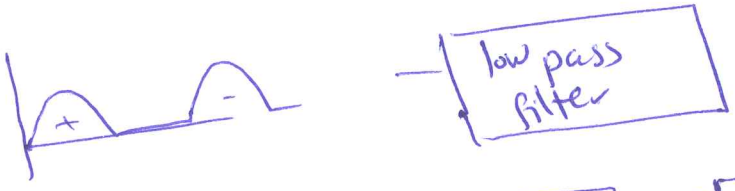
- Transformer:

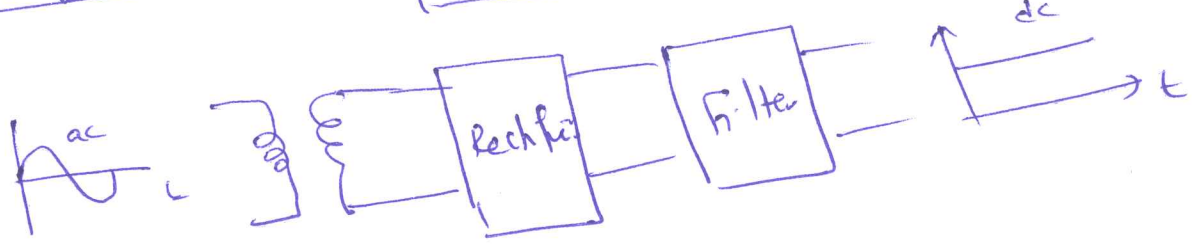


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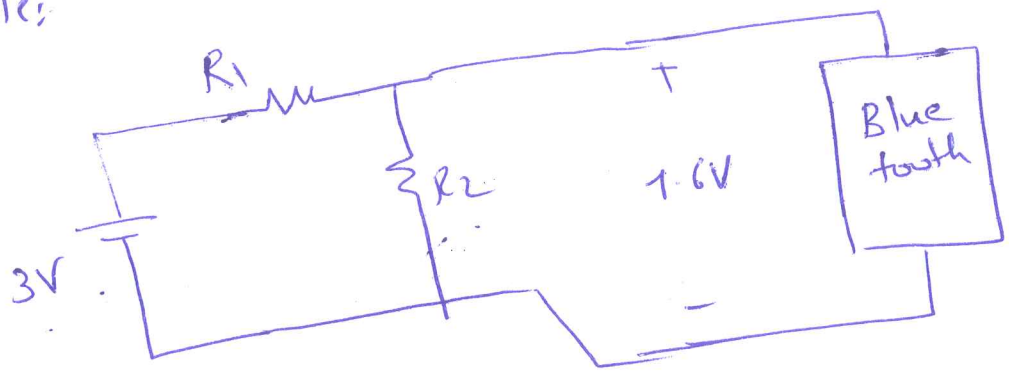


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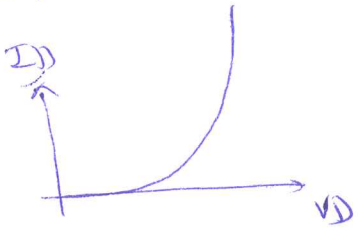


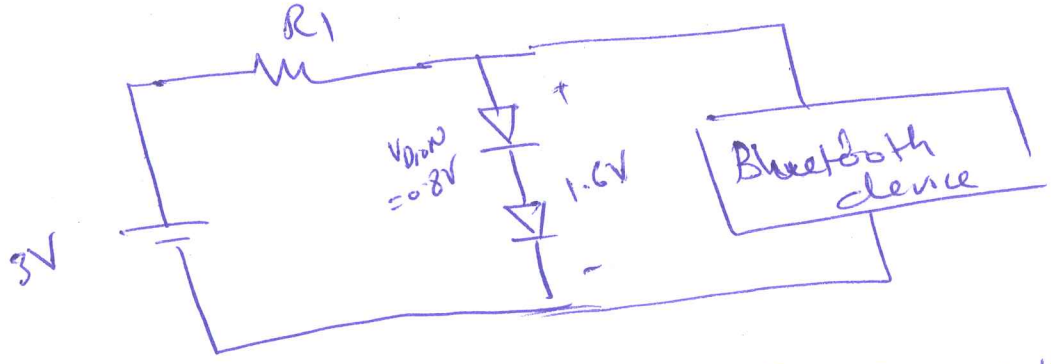
Example:



$$V_{R_2} = \frac{R_2}{R_1+R_2} 3V = 1.6V$$

the voltage across R_2 depends on the current and voltage





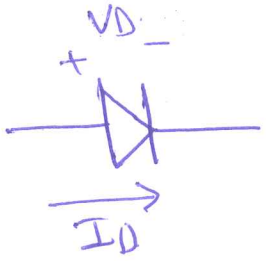
The voltage across each diode is a weak function of its current (forward Region)

* <u>Principle of diode Circuit Analysis:</u>
  - Begin by assuming certain state for all diodes.
  - Check the final result against these assumption. ($I_D > 0 \Rightarrow$ D is ON, $I_D < 0 \Rightarrow$ D is OFF)

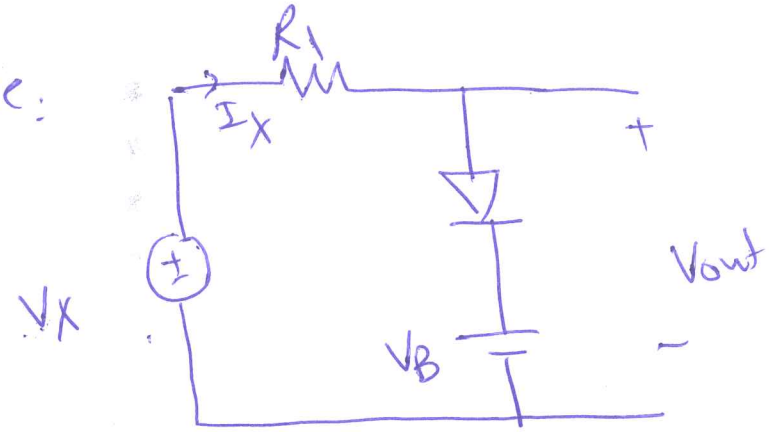
  - To find the transition level:
    * D is ON
    * Replacing D by its model

- $I_D = 0$, then we find the value of voltage (V_X) $\Rightarrow$ It is called Vtransition.

- Study two cases:-
  1) $V_X >$ Vtransition
  2) $V_X <$ Vtransition



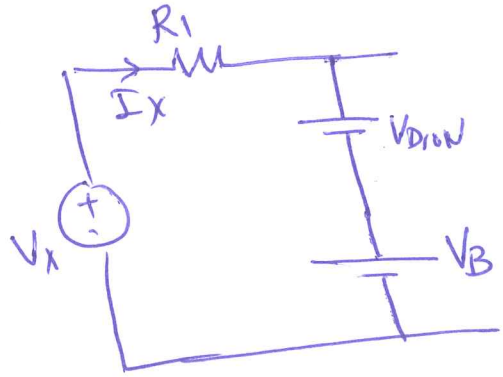
Example:



D is voltage constant model ($V_{D,ON}$)

plot I_X if V_X changes from $(-\infty, \infty)$

- D will be on in positive region
- Assume D is ON
- Replacing D by its equivalent Circuit



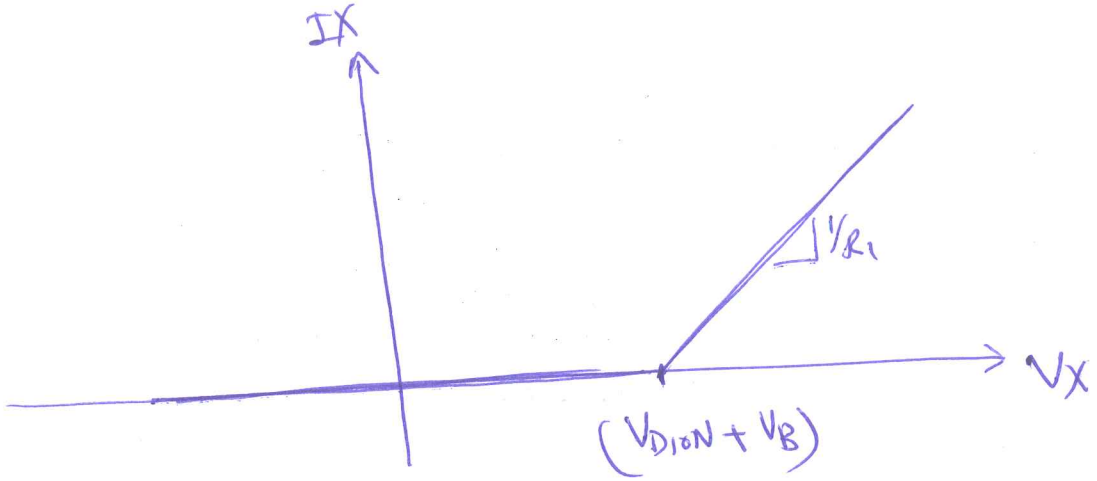
$$-I_X = \frac{V_X - (V_{D,ON} + V_B)}{R_1}$$

- when $I_X = 0$

$$V_{X_{transition}} = (V_{D,ON} + V_B)$$

- If $V_X > V_{tran} = (V_{D,ON} + V_B) \Rightarrow$ D is ON $\Rightarrow I_X = \frac{V_X - (V_{D,ON} + V_B)}{R_1}$

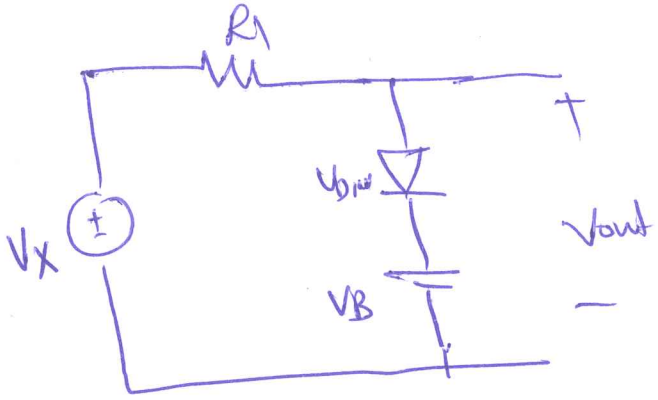
- If $V_X < (V_{D,ON} + V_B) \Rightarrow$ D is OFF $\Rightarrow I_X = 0$



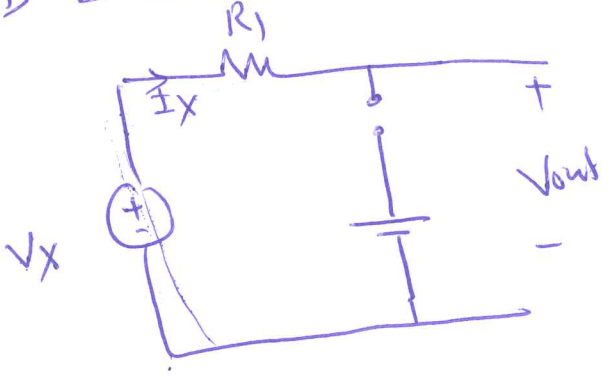
$V_X < V_{tran}$
D is OFF
$I_X = 0$

$V_X > V_{tran}$
D is ON
$I_X = \dfrac{V_X - (V_{D,ON} + V_B)}{R_1}$

Quiz
plot $V_{out} = f(V_X)$



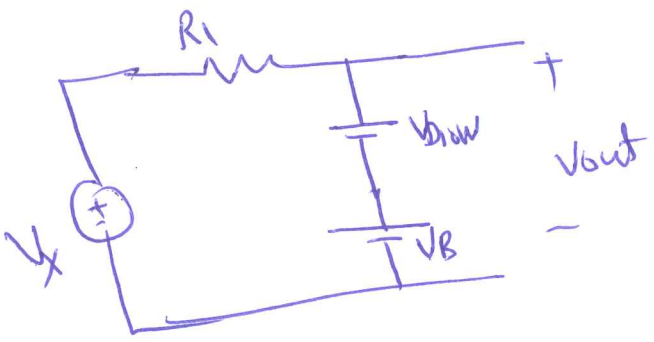
* If $V_X < (V_{D,ON} + V_B)$
$\Rightarrow$ D is OFF $\Rightarrow I_X = 0$

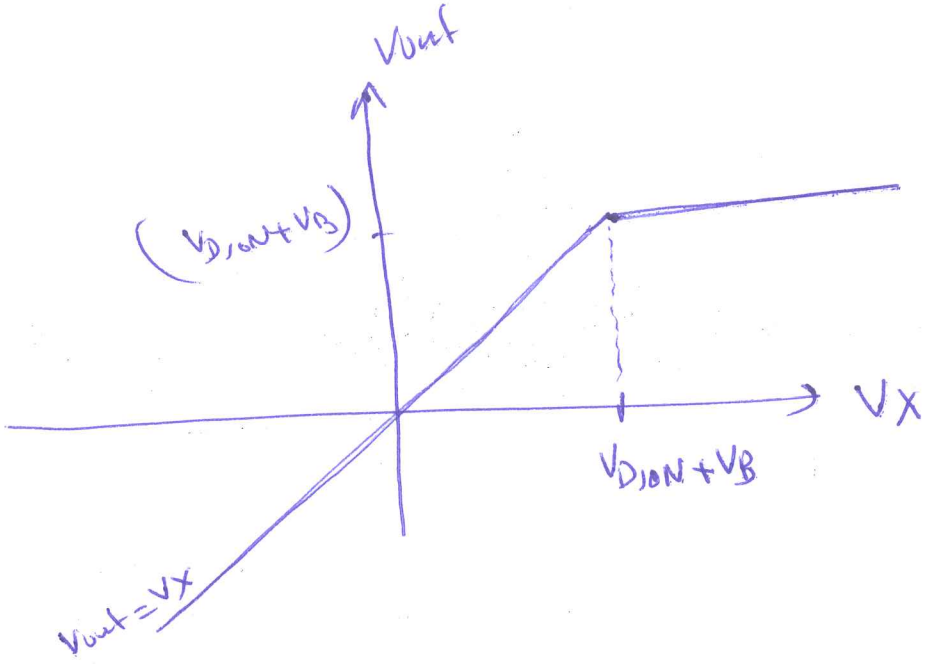


$-V_X + I_X R_1 + V_{out} = 0$

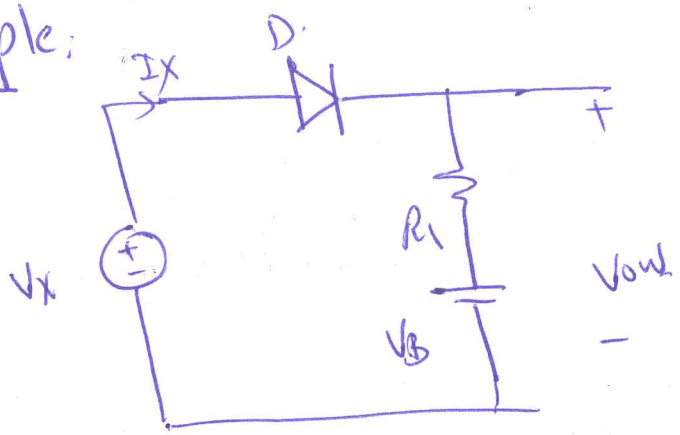
$\boxed{V_{out} = V_X}$

* If $V_X \geq (V_{D,ON} + V_B)$
$\Rightarrow$ D is ON
$\Rightarrow V_{out} = (V_{D,ON} + V_B)$





Example:

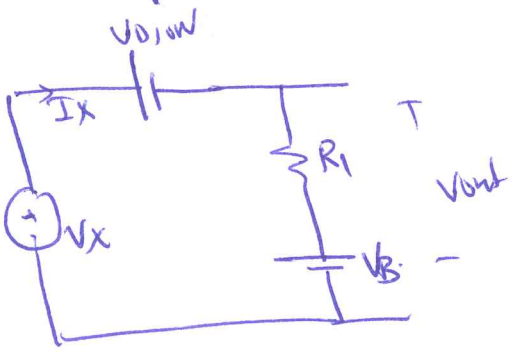


Using D → voltage Constant model to plot

$I_X = f(V_X)$

$V_{out} = f(V_X)$

- D will be ON in positive region (forward)



- Assume D is ON

KVL $-V_X + V_{D,ON} + I_X R_1 + V_B = 0$

$$I_X = \frac{V_X - (V_{D,ON} + V_B)}{R_1}$$

- when $I_X = 0 \Rightarrow V_{trans} = (V_{D,ON} + V_B)$

- If $V_X < (V_{D,ON} + V_B) \Rightarrow$ D is OFF

$\Rightarrow I_X = 0$.

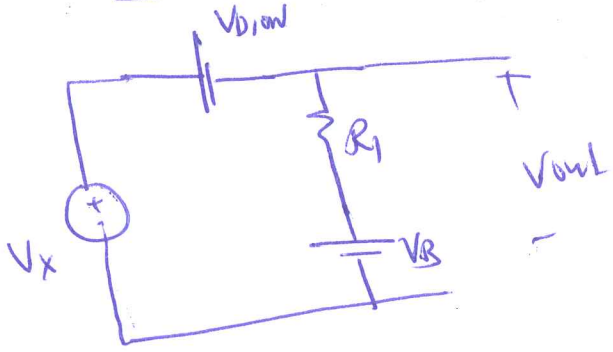
$V_{out} = I_X R_1 + V_B = V_B$

* $V_X > (V_{D,ON} + V_B) \Rightarrow$ D is ON

$\Rightarrow I_X =$

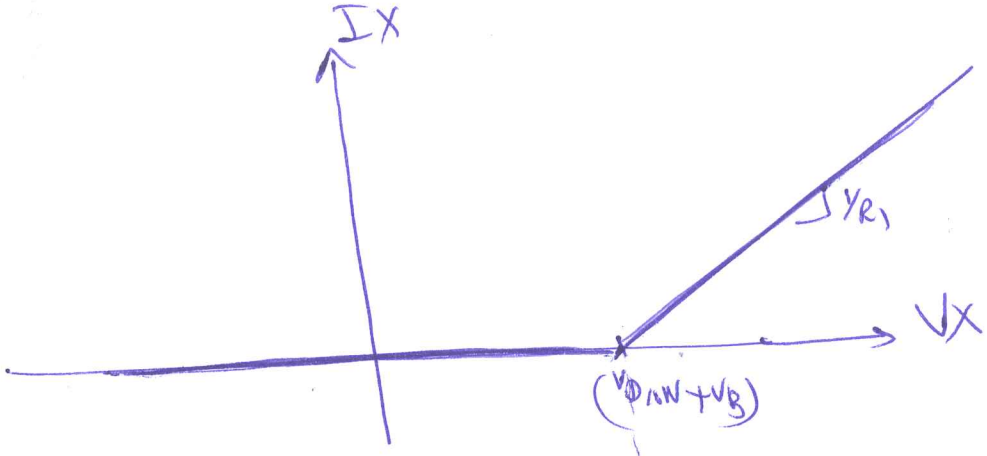
$$I_X = \frac{V_X - (V_{D,ON} + V_B)}{R_1}$$

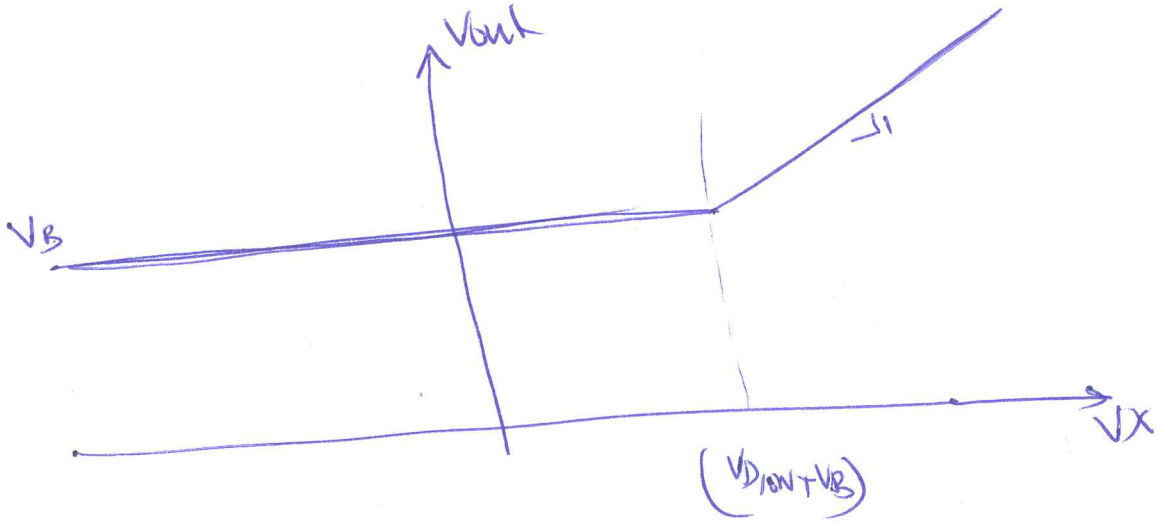




$-V_X + V_{D,ON} + V_{out} = 0$

$\Rightarrow (V_{out} = V_X - V_{D,ON})$





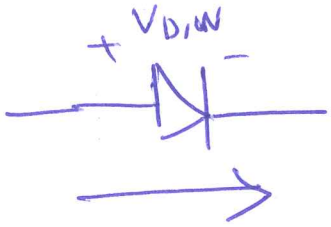
Today's lecture :

- Diode Circuit Examples
- Practical diode Circuits.

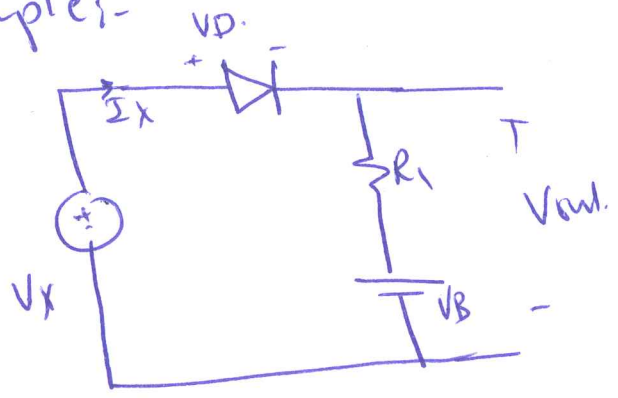
Review :

Three principles to analyze the diode Circuit

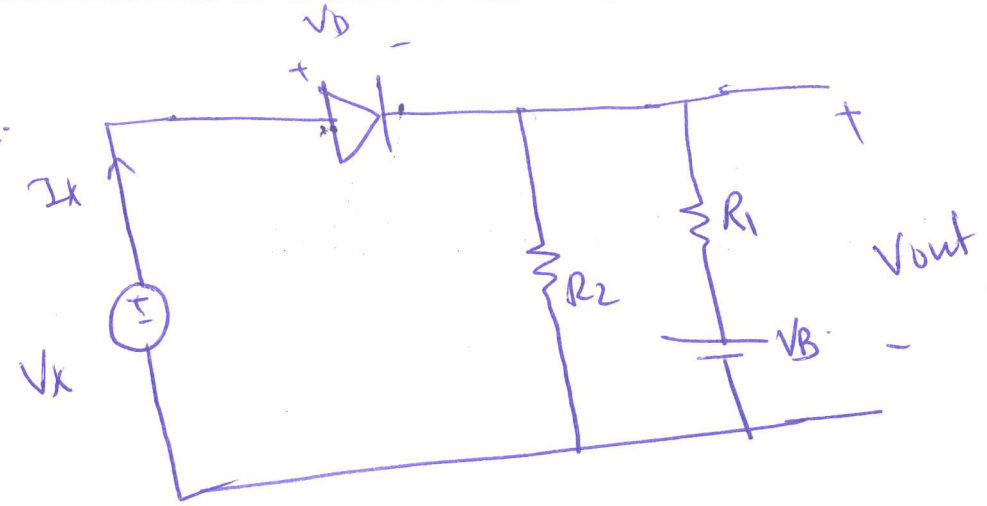
- Begin with an assumption for the state of each diode.
- The Final result must agree with these assumptions.
- If diode is about to turn on or off, its Voltage = $V_{D,ON}$ and its current = 0
- If a diode carries a current, the current must flow from anode to cathode.



Example:-



Example:

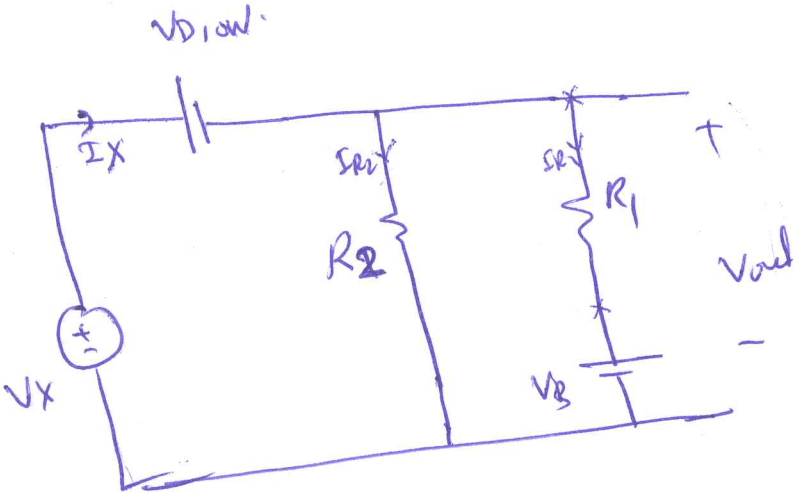


If D is voltage constant mode:

- plot i) $I_X = f(V_X)$
  ii) $V_{out} = f(V_X)$

V_X changes $(-\infty, \infty)$

- D is forward.
- Assume D is ON



KCL:

$$I_X = I_{R_2} + I_{R_1}$$

$$= \frac{V_{out}}{R_2} + \frac{V_{out} - V_B}{R_1} \longrightarrow (1)$$

KVL: $-V_X + V_{D,ON} + V_{out} = 0 \Rightarrow \boxed{V_{out} = V_X - V_{D,ON}} \rightarrow (2)$

Replacing (2, 1)

$$\Rightarrow I_X = \frac{V_X - V_{D,ON}}{R_2} + \frac{V_X - V_{D,ON} - V_B}{R_1}$$

$$I_X = (V_X - V_{D,ON})\left(\frac{1}{R_1} + \frac{1}{R_2}\right) - \frac{V_B}{R_1}$$

$$I_X = (V_X - V_{D,ON})\left[\frac{1}{R_1} + \frac{1}{R_2}\right] - \frac{V_B}{R_1}$$

To find transition level $\boxed{I_X = 0}$

$$(V_{X_1} - V_{D,ON})\left[\frac{1}{R_1} + \frac{1}{R_2}\right] = \frac{V_B}{R_1}$$

$$\Rightarrow V_{tran} = V_{X_1} = \frac{V_B}{R_1} + V_{D,ON}\left[\frac{R_1 + R_2}{R_2}\right]$$

If $V_X > V_{X_1} \Rightarrow$ D is ON

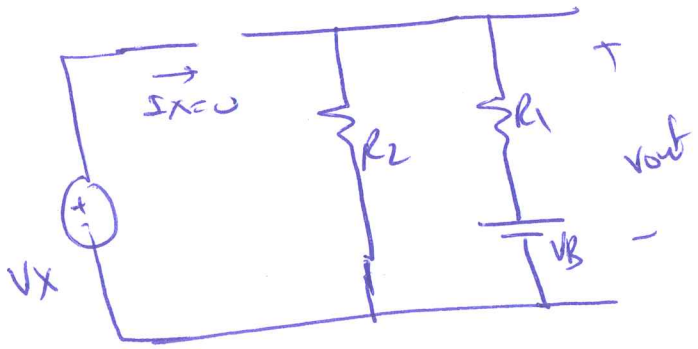
$$\Rightarrow I_X = (V_X - V_{D,ON})\left[\frac{1}{R_1} + \frac{1}{R_2}\right] - \frac{V_B}{R_1}$$

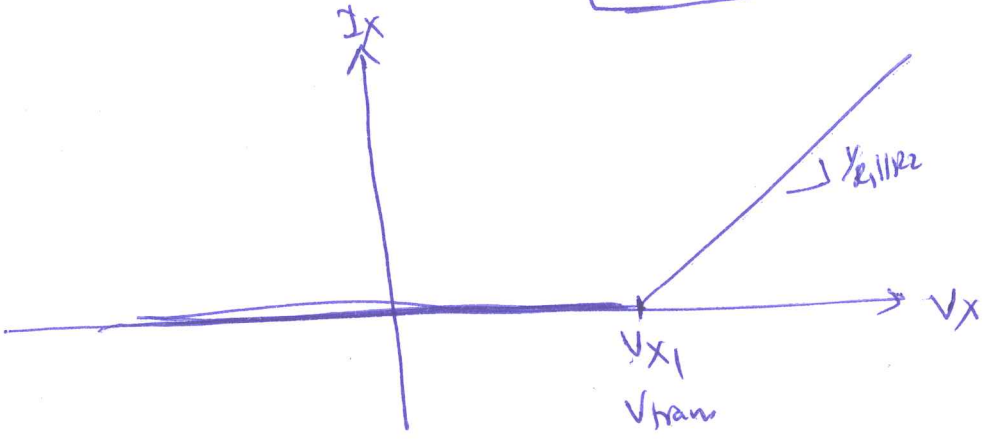
$$\Rightarrow V_{out} = V_X - V_{D,ON}$$

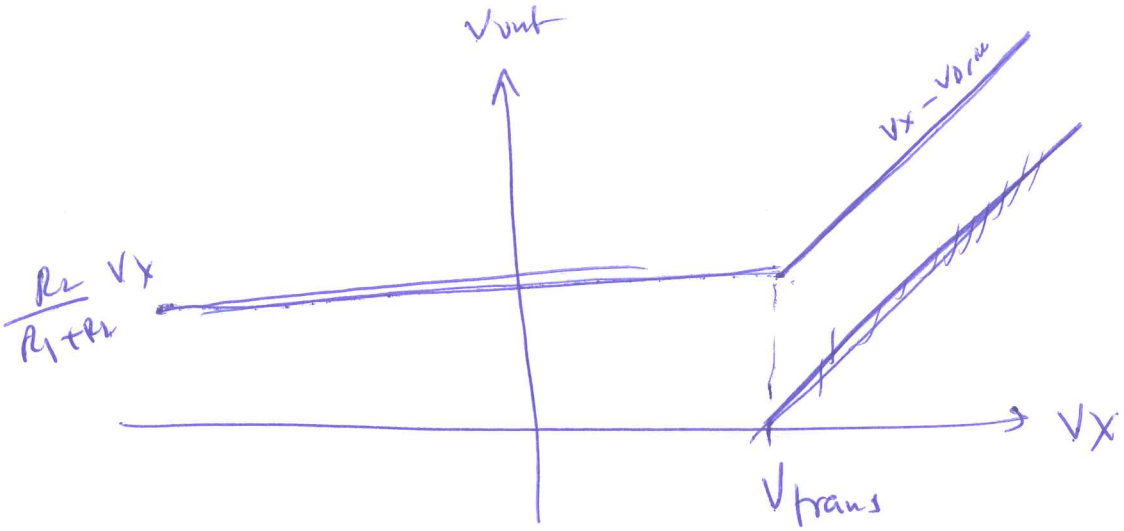
If $V_X < V_{X_1} \Rightarrow$ D is OFF

$$I_X = 0$$

$$V_{out} = V_{R_2} = \frac{R_2}{R_1 + R_2} V_B$$







for D is on $V_X > V_{trans} \Rightarrow V_{out} = V_X - V_{D,on}$

D is OFF $V_X < V_{trans}$ $V_{out} = \frac{R_2}{R_1+R_2} V_X$

Practical Diode Circuits

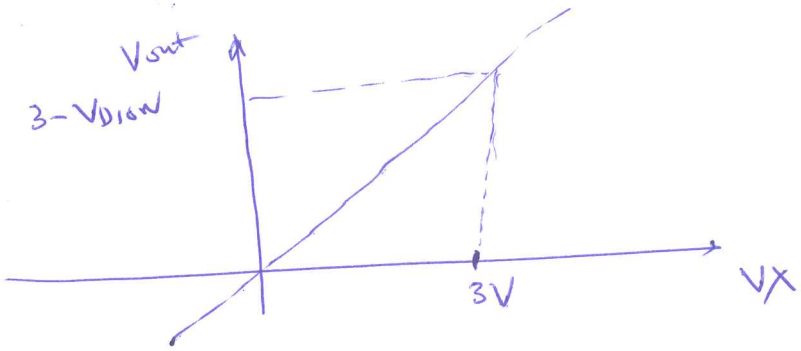
1) Rectifier
2) Limiter
3) Voltage doubler
4) level shifts

Basic Concepts :

- Analysis Circuit to obtain.
  - * I-V Characteris
  - * V-V Charact.
- Time Response

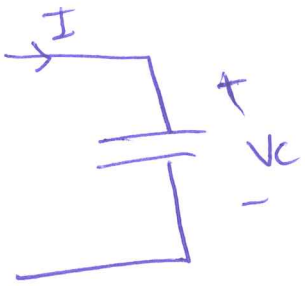
2) Concept of tracking:

$V_{out} = V_X - V_{D,ON}$

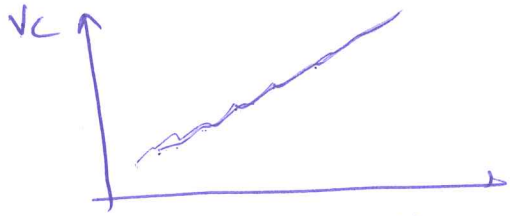


that means Vout tracks Vx with a constant difference. ($V_{D,ON}$)

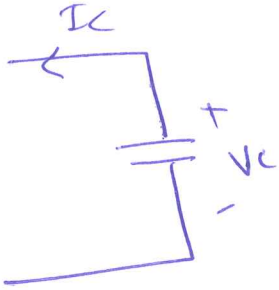
3) Quick Review of Capacitor



Charging: push I in the Capacitor



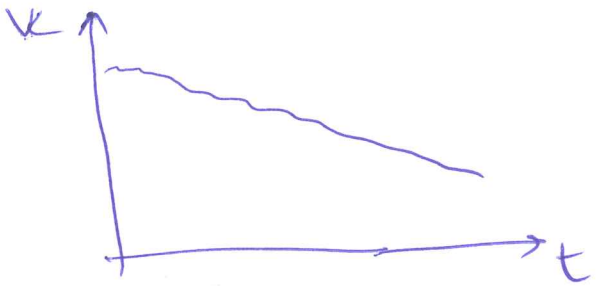
By pushing the current into C ⇒ its voltage increasing



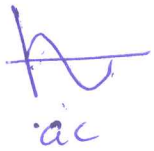
discharging: push I out the capacitor.

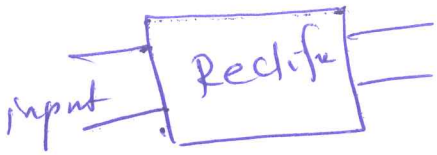
By push I out of Capacitor its voltage decreases

$$I = C\frac{dV}{dt}$$



Rectifier:







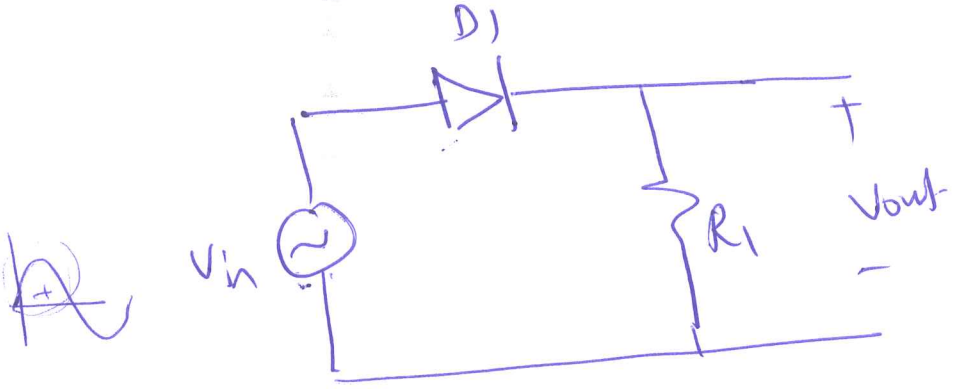
dc



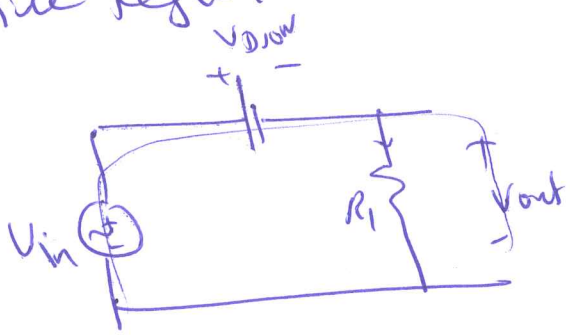
-1) Halfwave Rectifier

1) $V_{out} = f(V_{in})$
2) sketch $V_{out}(t)$

D is voltage constant model



- D will be pN in positive Region
- Assume D is ON



KVL,

$-V_{in} + V_{D,ON} + I_D R_1 = 0$

when $I_D = 0$

$\Rightarrow \boxed{V_{in} = V_{tran} = V_{D,ON}}$

If $V_{in} < V_{D,ON} \Rightarrow$ D is OFF $\Rightarrow I_D = 0 \Rightarrow \boxed{V_{out} = 0}$

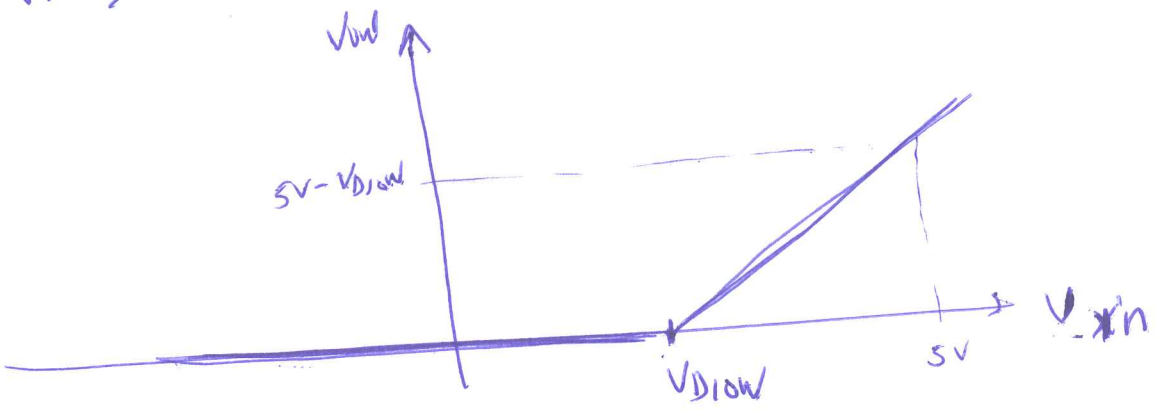
If $V_{in} > V_{D,ON} \Rightarrow$ D is ON $\Rightarrow$

KVL: $-V_{in} + V_{D,ON} + V_{out} = 0$

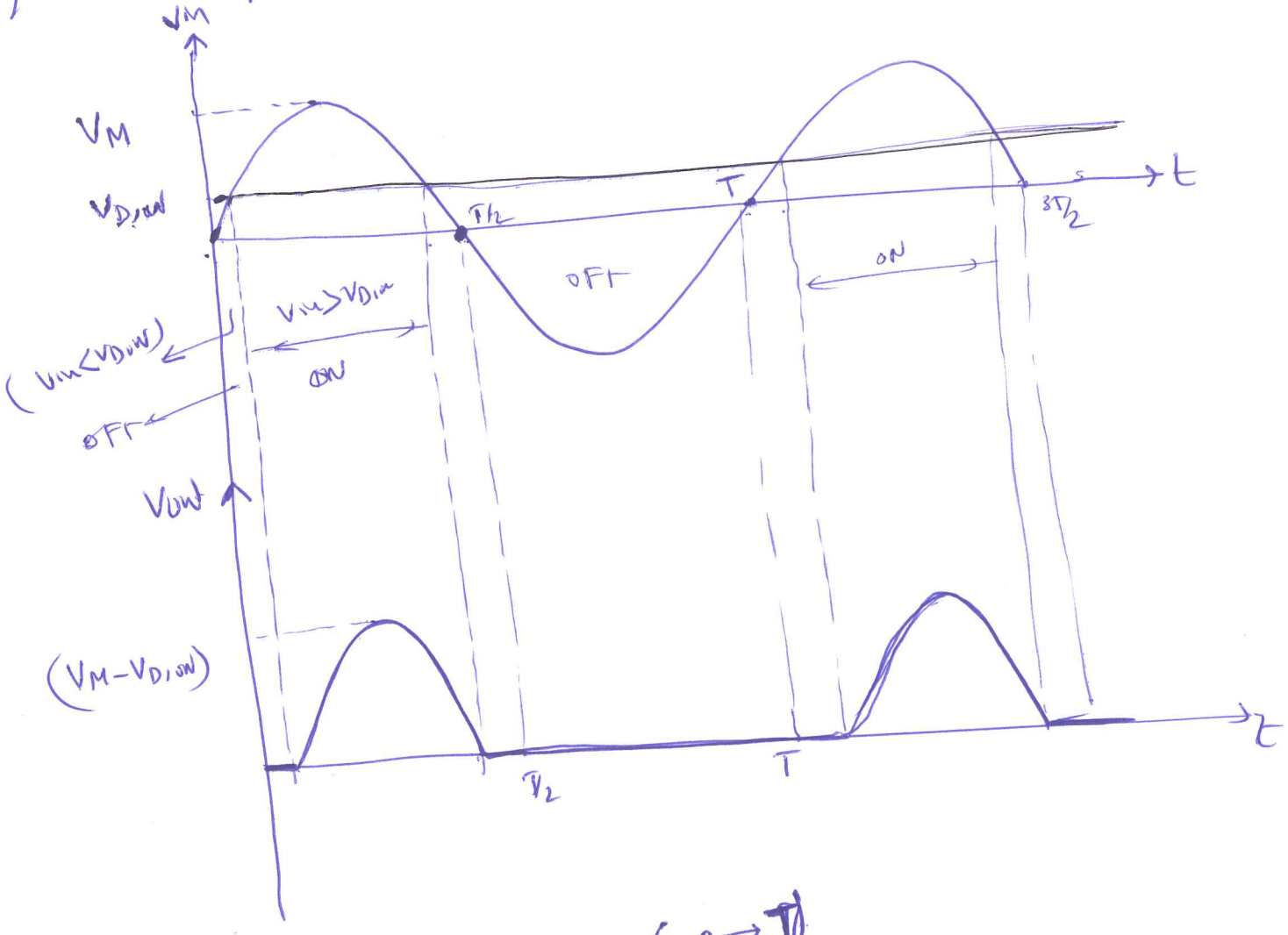
$\Rightarrow \boxed{V_{out} = V_{in} - V_{D,ON}}$

when $V_{in} < V_{D,ON}$ ⇒ D is OFF ⇒ $V_{out} = 0$

$V_{in} > V_{D,ON}$ ⇒ D is ON ⇒ $V_{out} = V_{in} - V_{D,ON}$



2) Time Response $V_{out}(t)$



$V_{in} = V_M \sin \omega t$ $(0 \rightarrow T)$

$V_{out} = (V_M - V_{D,ON})$ $(0 \rightarrow T/2)$

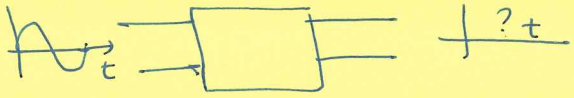
lect. 10

Today's lect.

- Halfwave Rectifier with smoothing Cap.
- Full wave Rectifier

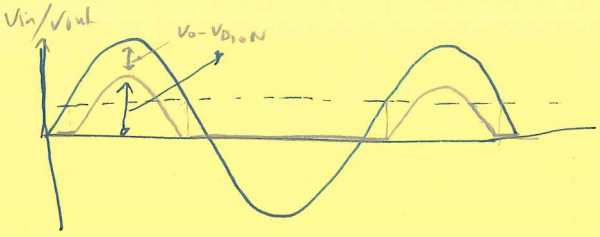
Review of lec. 9

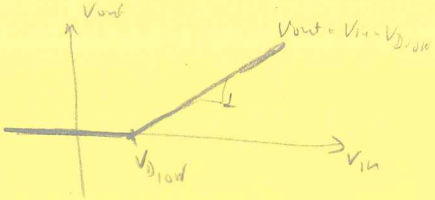
- Time Response



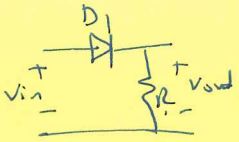
- Halfwave Rectifier

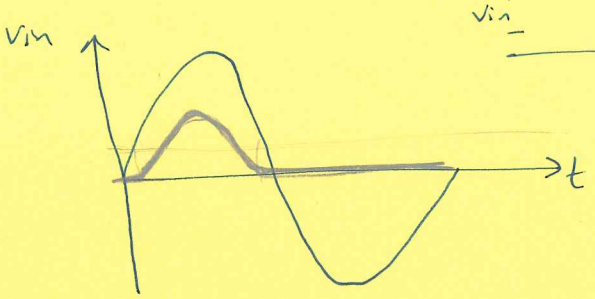






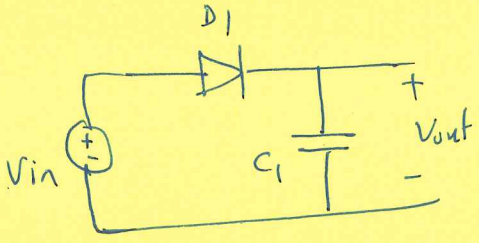
- Halfwave Rectifier

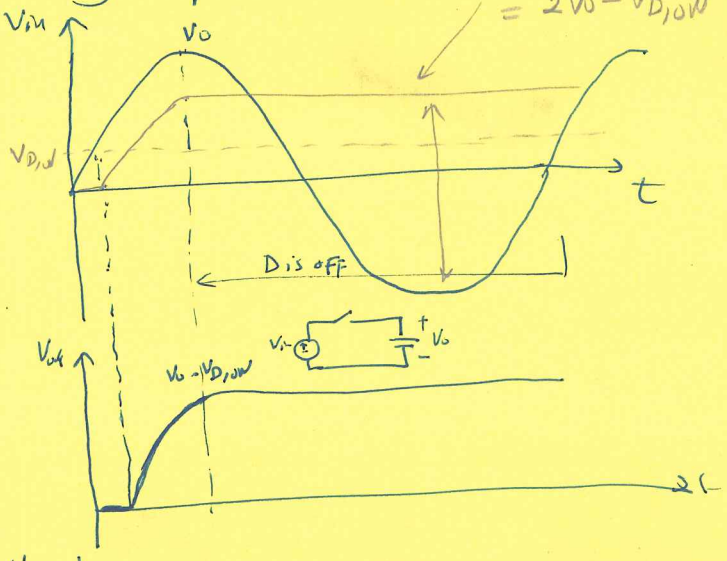




we see that the output is dc but its changes its value.

- Halfwave Rectifier with smoothing Cap.

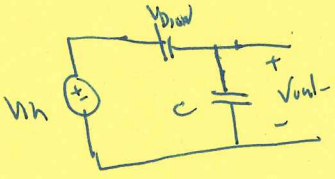




max breakdown voltage = $2V_o - V_{D,ON}$

Remark: To charge C will push I into C
: To discharg " " : I out C

when $V_{in} > V_{D,ON} \Rightarrow D_1$ is ON $\Rightarrow$



$V_{out} = V_{in} - V_{D,ON}$

* When $V_{in} < V_{D,ON} \Rightarrow$ D is OFF
but the capacitance still holds the charge as before

$V_{out} = V_o - V_{D,ON}$

- Reverse voltage across D_1

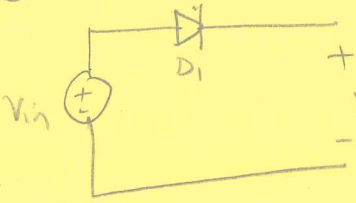
So, in order the circuit to work in good manner we have to avoid the reverse voltage across D_1

max breakdown voltage

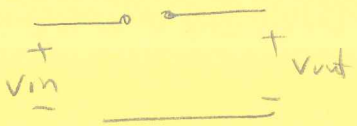
$$V_{Brk} = 2V_o - V_{D,ON}$$

- Two points

1) Why we use R_1 in the orginal circuit ?



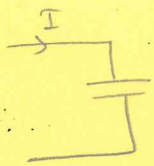
If D is OFF



Vout ≠ 0
not define

2) Can we plot input/out charact for the rectifier with Capacitor

In, general, It is difficult

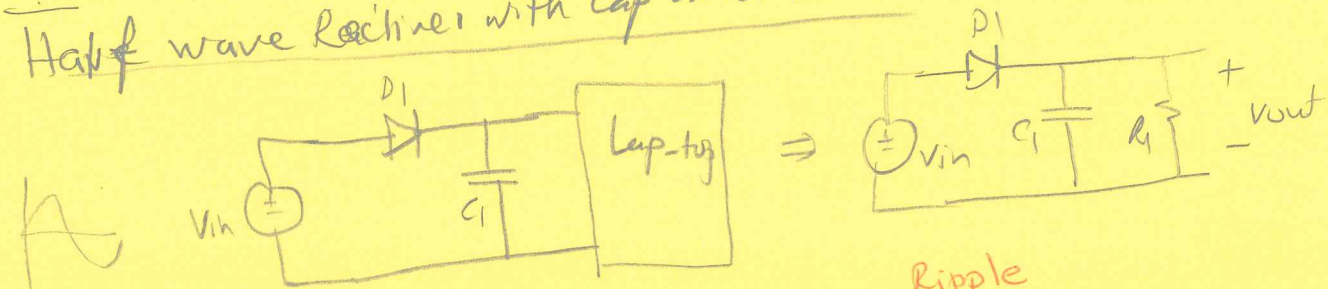


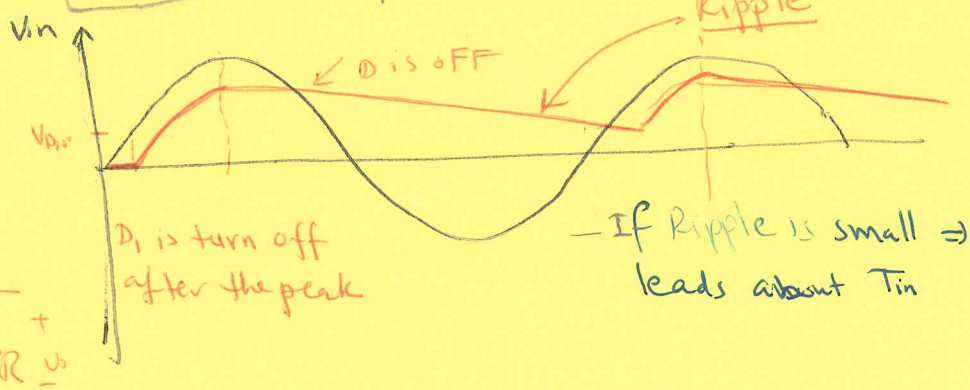
$$I = C\frac{dV}{dt}$$

because the circuit has storge device that depends on time

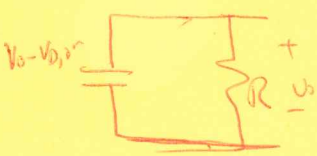
So, we generaly, we don't want to plot the Input/output charact.

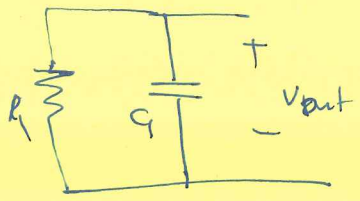
Half wave Rectifier with cap and Load

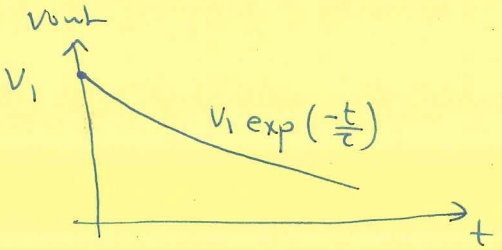




- If Ripple is small ⇒ decay leads about Tin







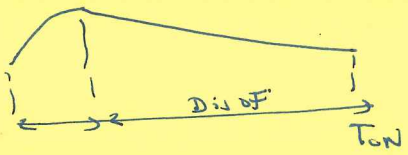
initial value on $C_1 = V_1$

* If $t \ll t_1 \Rightarrow V_1 \exp\frac{-t}{\tau} \approx V_1\left[1 - \frac{t}{\tau}\right]$

For half wave Rectifier

$$V_{out} = (V_0 - V_{D,ON})\left(1 - \frac{t}{\tau}\right) \rightarrow \text{Behaviour when D is OFF}$$

$$V_{out}(t = T_{in}) = (V_0 - V_{D,ON})\left(1 - \frac{T_{in}}{\tau}\right)$$



Ripple amplitude

$$= V_{out}\Big|_{t=0} - V_{out}\Big|_{t=T_{in}}$$

$$= (V_0 - V_{D,ON})\frac{T_{in}}{\tau}$$

$$= \frac{(V_0 - V_{D,ON})}{R_1 C_1 f_{in}}$$

$\tau = R_1 C_1$

$T_{in} = 1/f_{in}$

The dc value of Vout

$$V_{out} = \begin{cases} V_p \sin \omega t & 0 < t < T/2 \\ 0 & T/2 < t < T \end{cases}$$

$$V_{0\,average} = \frac{1}{T}\int_0^T V_{out}(t)\,dt = \frac{1}{T}\int_0^{T/2} V_p \sin\omega t\,dt$$

$$= \frac{1}{T}\frac{V_p}{\omega}\left[-\cos\omega t\right]_0^{T/2}$$

$$= \frac{V_p}{\pi}$$

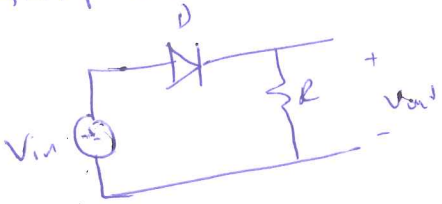
lect. 11

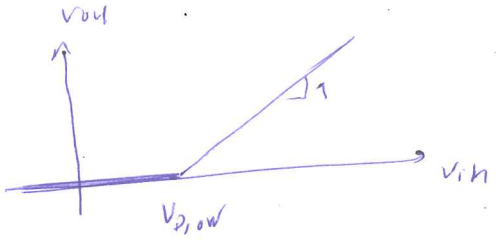
Today's lect.

- Full wave Rectification
  - Basic structure
  - Behavior with Load Capacitor and Resistance

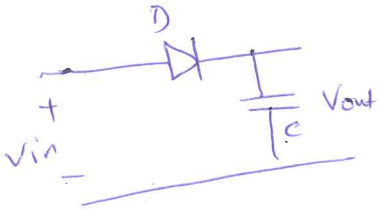
Review of lect. 10

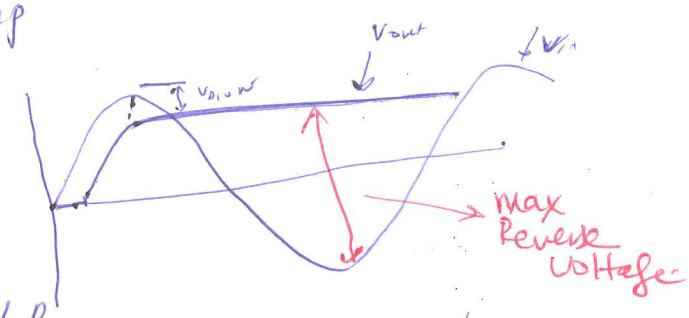
- Halfwave Rectifier



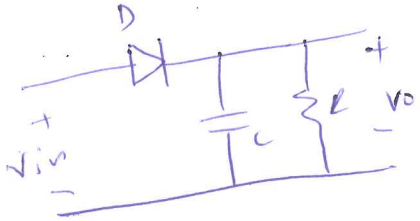


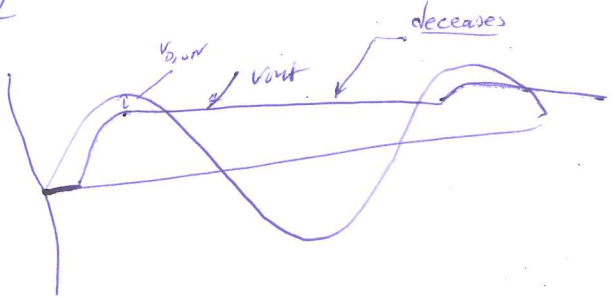
- Halfwave Rectifier with Cap





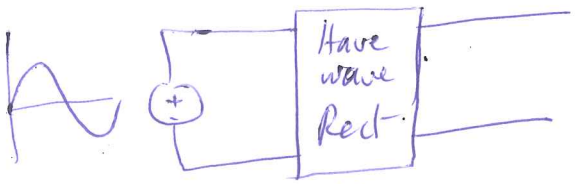
- Halfwave Rect with C and R





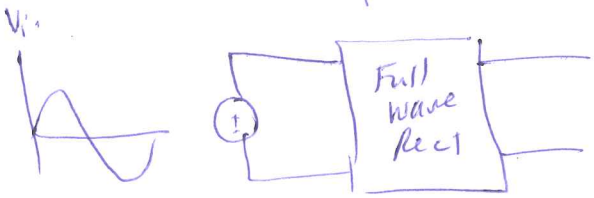
$$\text{Ripple} = \frac{V_o - V_{D,ON}}{R_1 C_1 f_{in}}$$

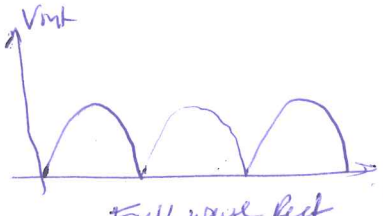
* Full Wave Rectifier



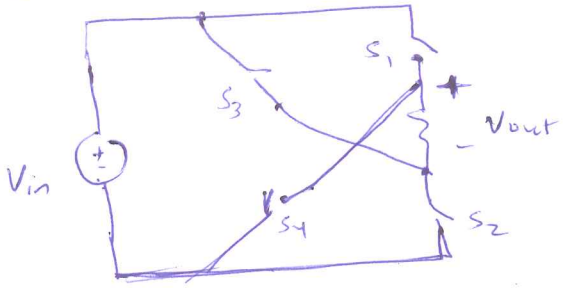








Observations -



1) If S_1, S_2 are ON

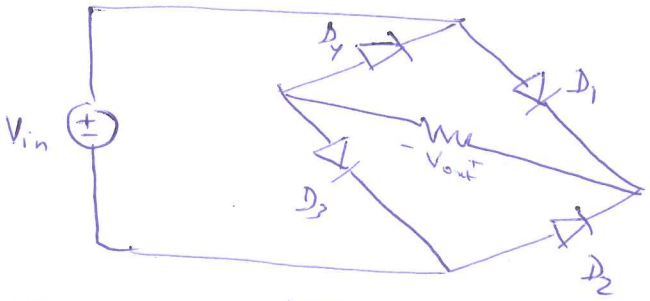
$\Rightarrow$ $V_{out} = V_{in}$

2) If S_3 and S_4 are

$\Rightarrow$ $V_{out} = -V_{in}$

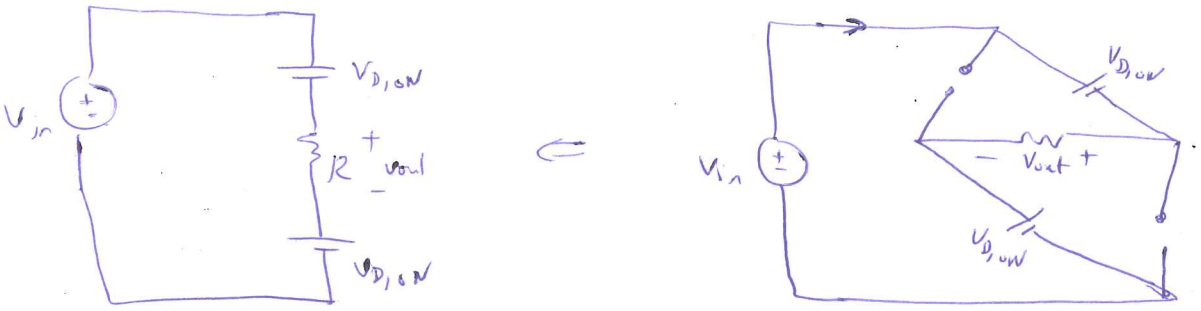
Replacing the switch by diodes so in this case the circuit is called Full wave Rectifier

Full wave Rectifier (Diode Bridge)



Begin with Vin very positive

D_1, D_3 are ON , (D_2, D_4) are OFF



$$-V_{in} + V_{D,ON} + V_{out} + V_{D,ON} = 0$$

$$V_{out} = V_{in} - 2V_{D,ON}$$

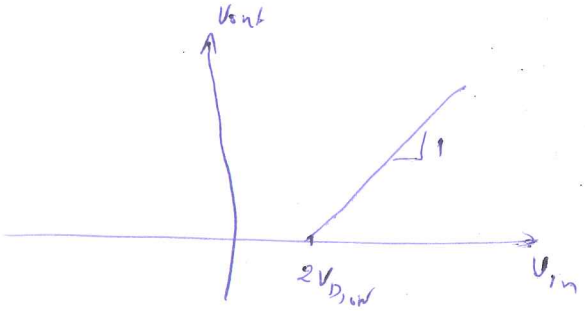
for (+) Region

for $V_i > 2V_{D,ON}$ $\Rightarrow$ D_1, D_3 are ON

$$\Rightarrow V_{out} = V_{in} - 2V_{D,ON}$$

for $V_i < 2V_{D,ON}$, D_1, D_3 are OFF

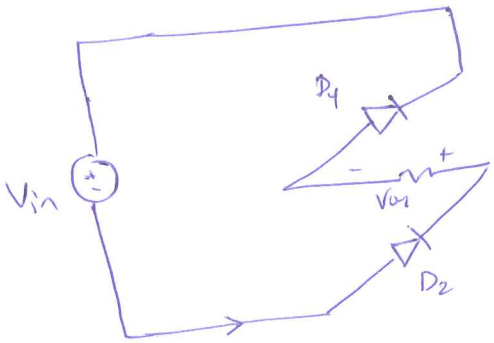
$$V_{out} = 0$$

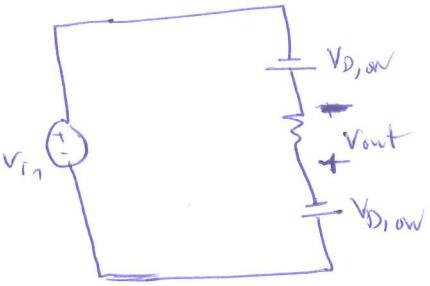


For negative Region :-

If V_{in} is sufficiently negative (D_1, D_2) are ON
(D_1, D_3) are OFF

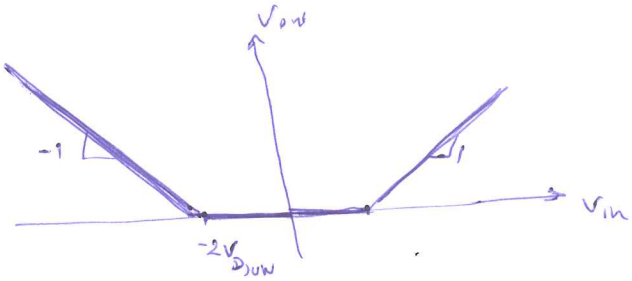
The circuit becomes





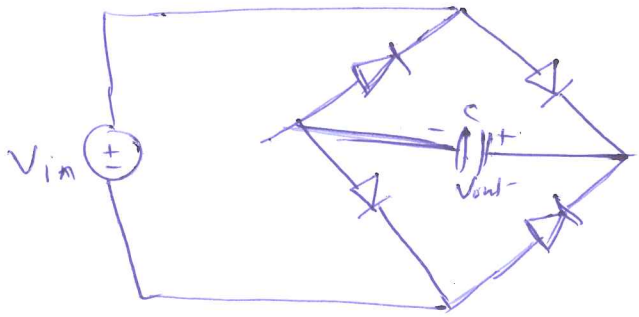
$$-V_{in} - V_{D,ON} - V_{out} - V_{D,ON} = 0$$

$$\boxed{V_{out} = -V_{in} + 2V_{D,ON}}$$

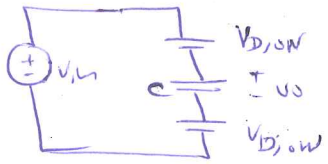


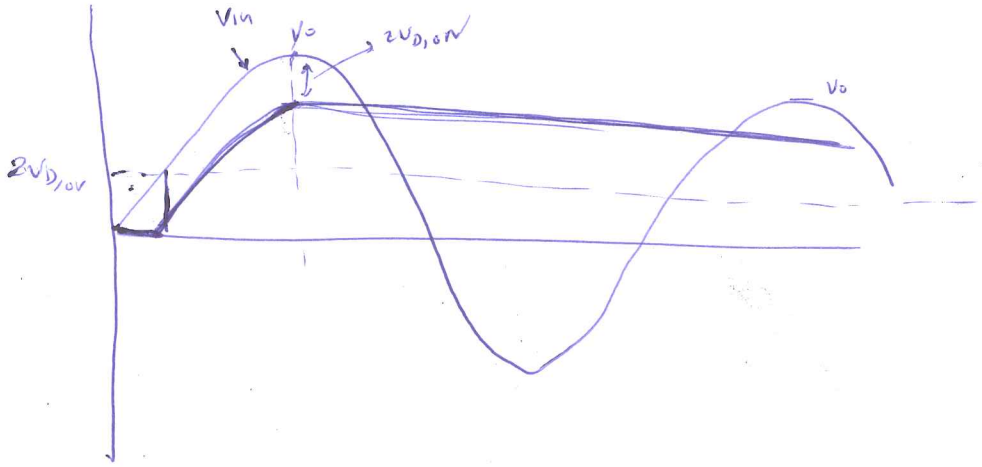
Full wave Rectifier with Cap



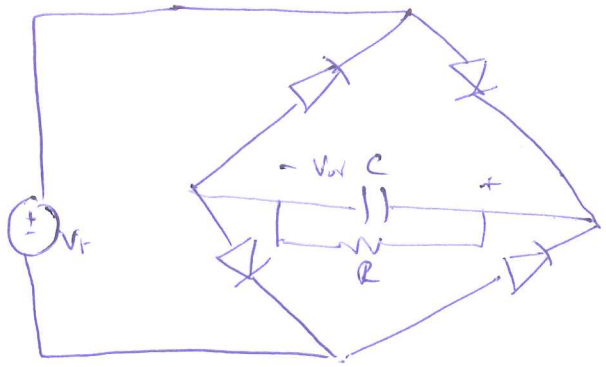


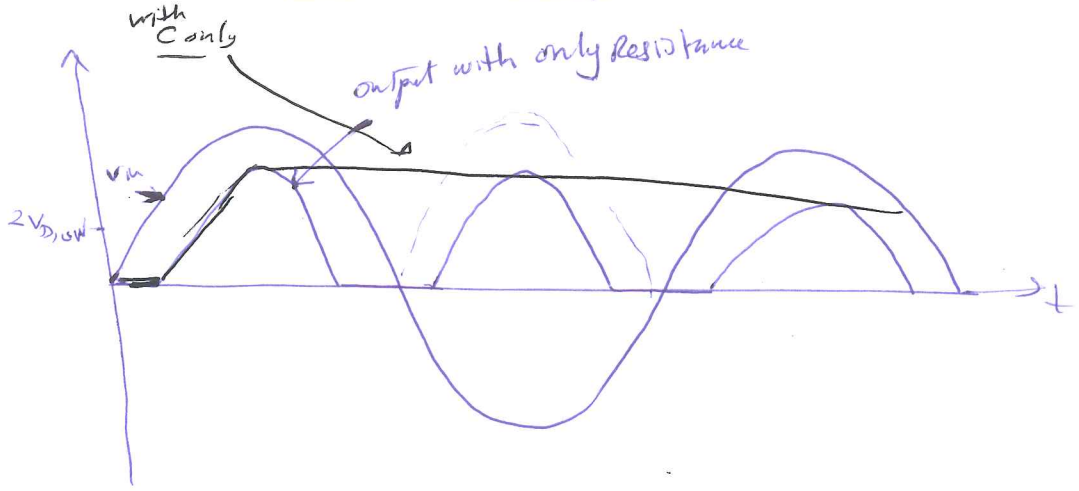
for $V_i > 2V_{D,ON}$

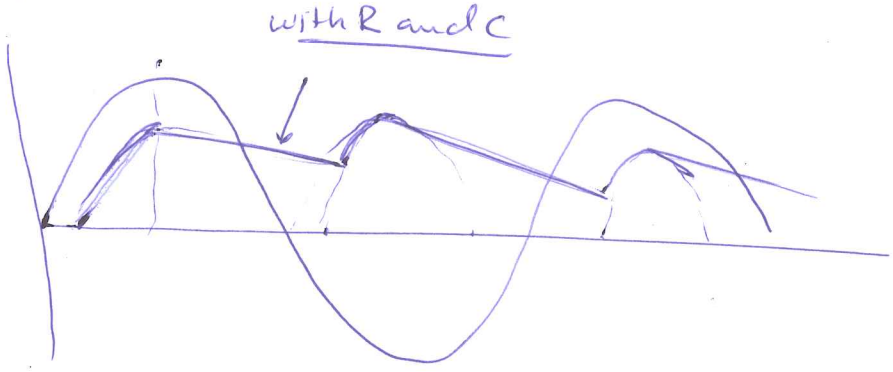




Full wave
with Cand Res
as load.







- Ripple amplitude
  - for halfwave Rectifier = $\frac{V_o - V_{D,on}}{R_1 C_1} T_{in}$
  - for Full wave Rectifie = $\frac{V_o - 2V_{D,on}}{R_1 C_1} \cdot \frac{T_{in}}{2}$

Ripple for Full wave $\cong \frac{1}{2}$ half wave Rectifier

$$f_{out} = \begin{cases} f_{in} & \text{for halfwave} \\ 2f_{in} & \text{for Full wave} \end{cases}$$

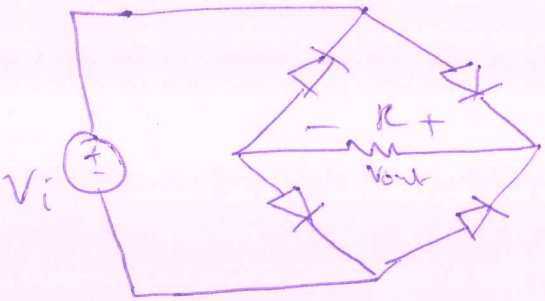
diode

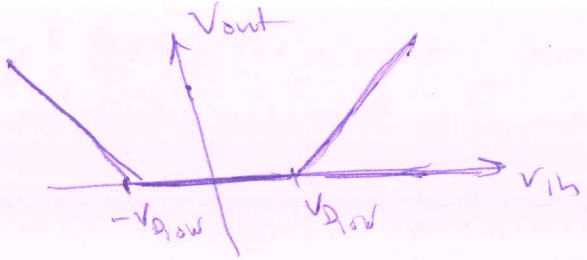
Today's lect.

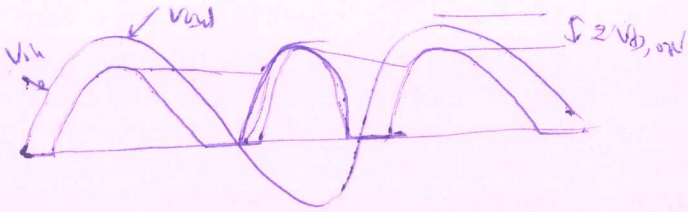
- limiting Circuit
- Voltage doubler
- level shift

Review of lect 11

- Full wave Rectifier

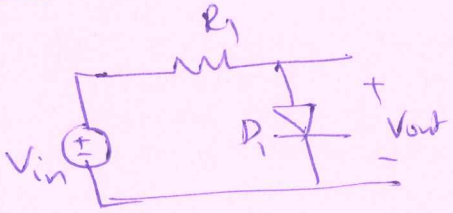


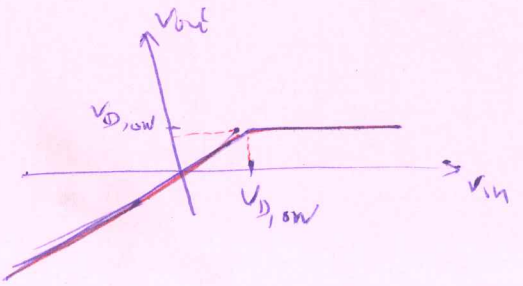


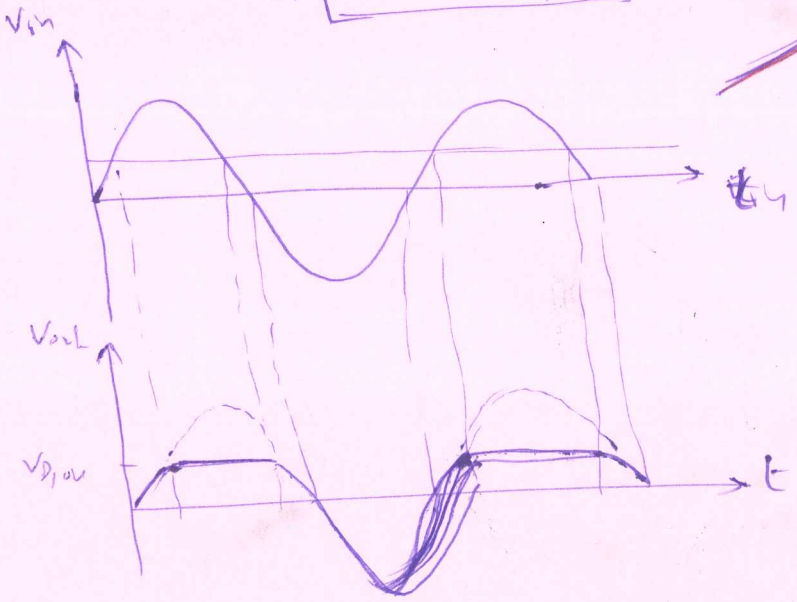


* Limiting Circuits:

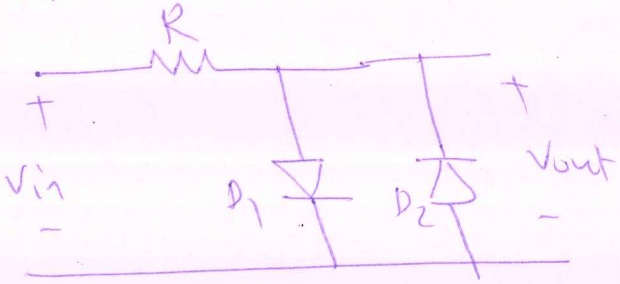
Try this

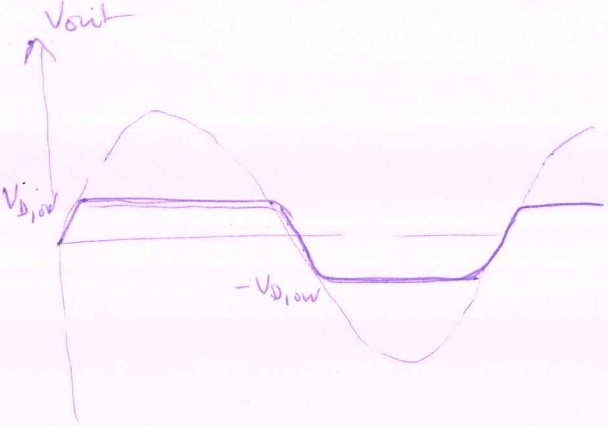




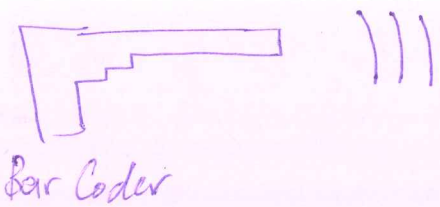


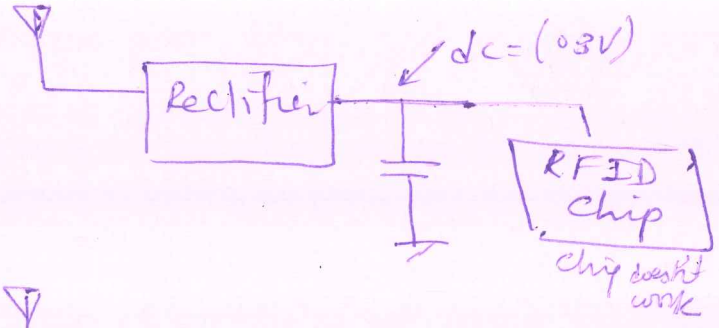
- Limiter

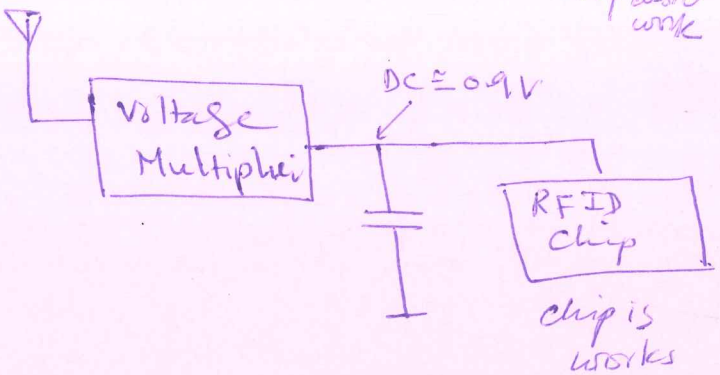




Example: RFID system



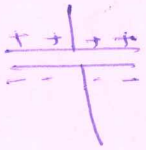




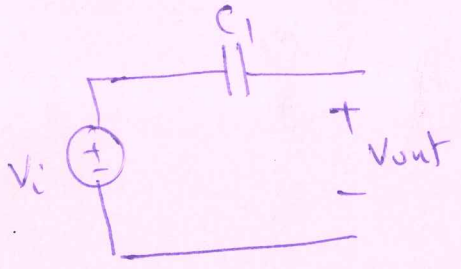
- Voltage doubler :-

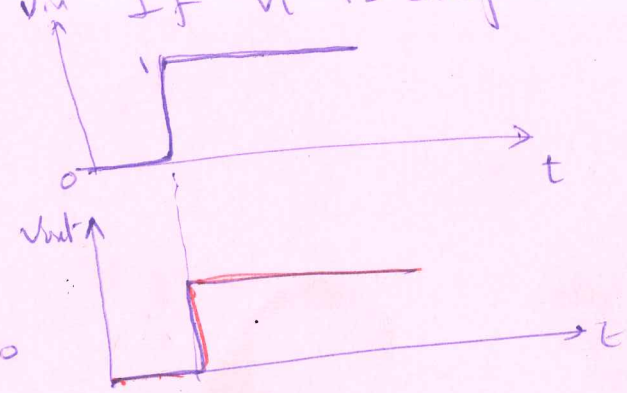
* Observations:

① To charge a Capacitor, we need to placed positive charge on one plate and negative charge on the other.



②

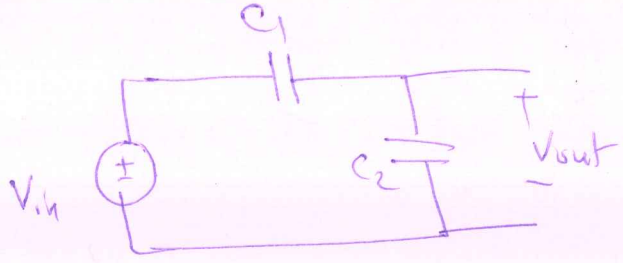




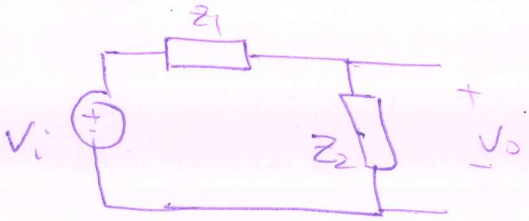
- Since the circuit is open the C doesn't charge.
- If C doesn't charge $V_C = 0$

$\Rightarrow$ $\boxed{V_{out} = V_i}$

(3)



Using voltage divide

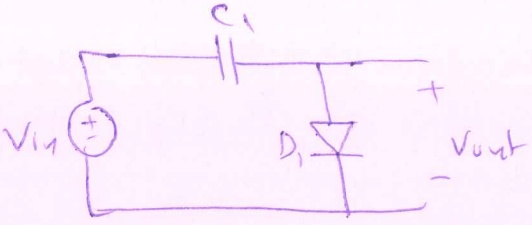


$$\Rightarrow \frac{V_{out}}{V_{in}} = \frac{Z_2}{Z_1+Z_2}$$

for Capacitance $Z = \frac{1}{sC}$

$$\frac{V_{out}}{V_{in}} = \frac{\frac{1}{sC_2}}{\frac{1}{sC_1}+\frac{1}{sC_2}} = \frac{C_1}{C_1+C_2}$$

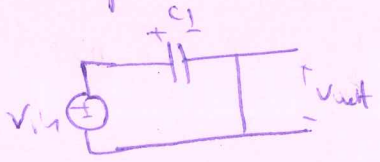
(4)



- Assume initial condition so $V_{C_0} = 0$.

for ⊕ Region ⇒ D is ON

⇒ Capacitor will charge



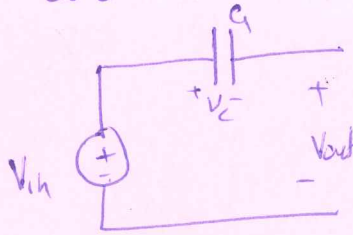
$V_{out} = 0$

$V_{C_1} = V_{in}$

after the peak

the diode becomes open

the circuit becomes

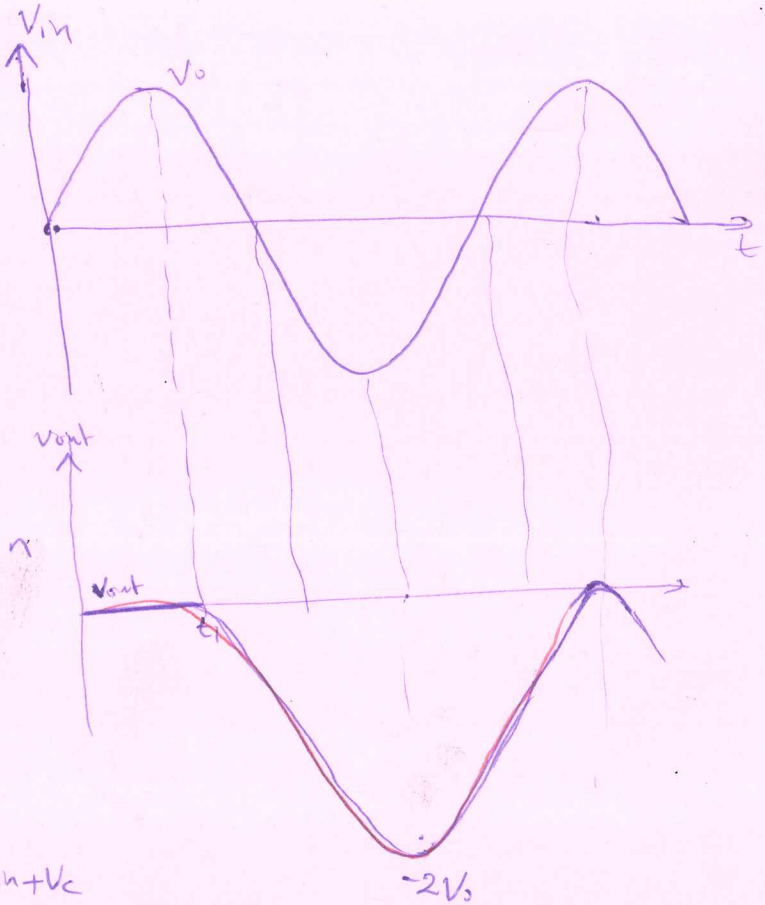


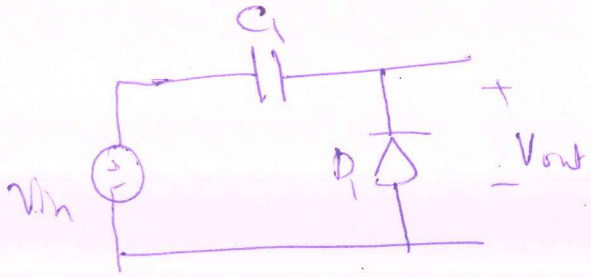
$\Rightarrow V_{out} = V_{in} + V_c$

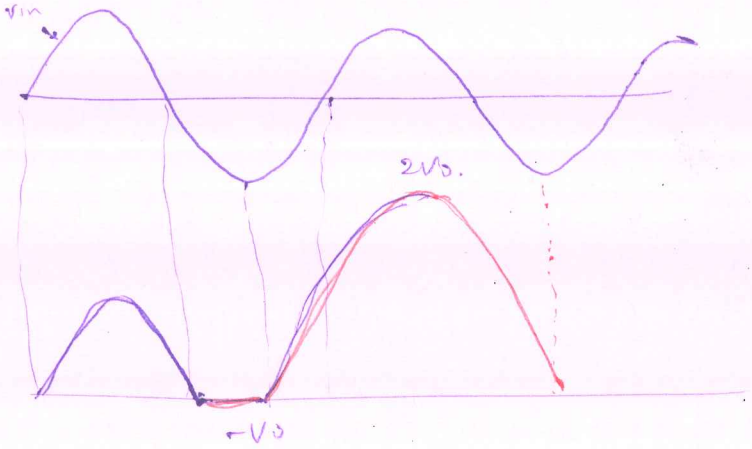
@ the peak:

$V_{out} = -2V_0$

- Assume D is ideal

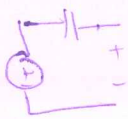






for ⊕ Region

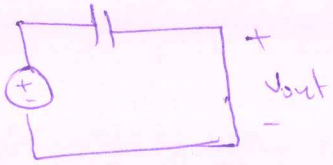
- If the D is OFF



⇒ $\boxed{V_{out} = V_{in}}$

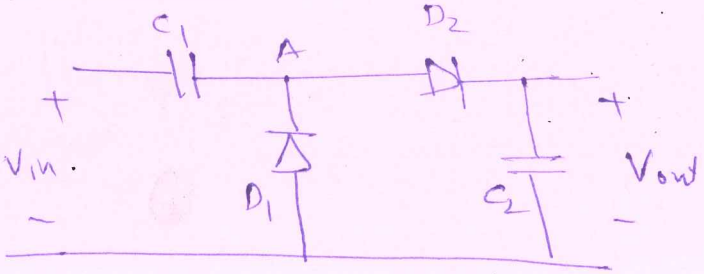
- for ⊖ Regin

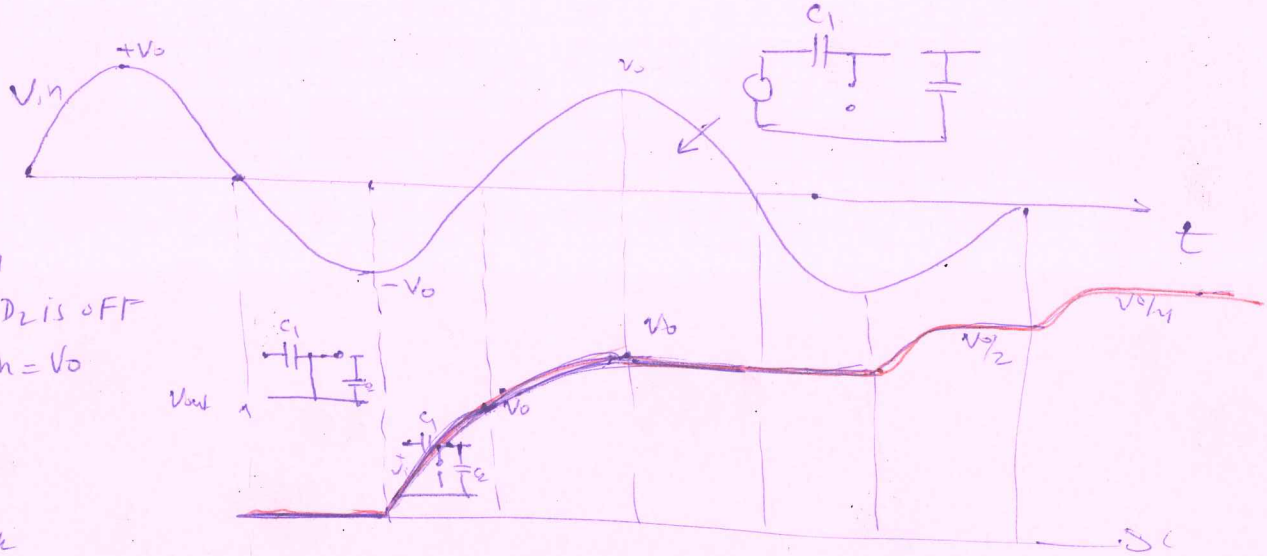
D is ON ⇒ D is short



⇒ Vout = 0

Voltage doubler





for ⊖ region

D_1 is ON, D_2 is OFF

$V_{C1} = V_{in} = V_o$

$V_{out} = 0$

assume $C_1 = C_2$

after the peak

$\Rightarrow V_{out} = \frac{C_2}{C_1 + C_2} V_{in}$

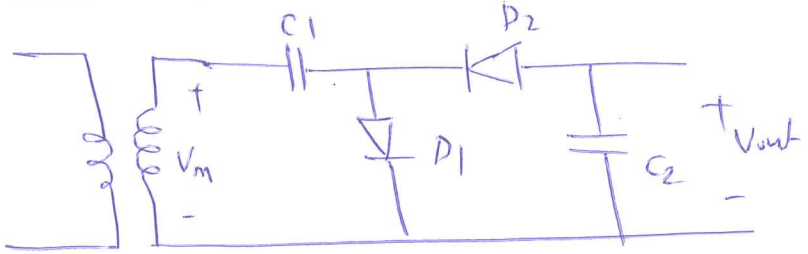
Voltage Multiplier Circuits

- Voltage Multiplier circuits are used to maintain low transformer peak voltage by stepping up the peak output voltage to two, three, four, or more times the peak rectified voltage.

Voltage Multiplier Circuits

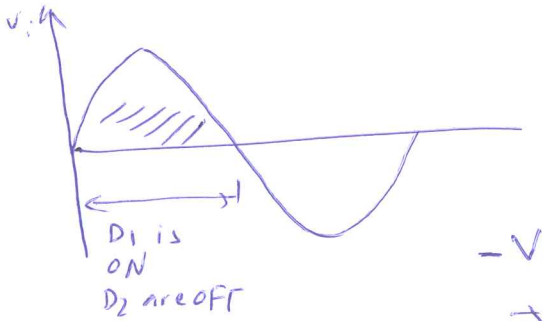
- Voltage doubler ($2V_m$)
  - Half-wave Voltage Doubler
  - Full wave Voltage Doubler
- Voltage Tripler ($3V_m$) and Quadrapler ($4V_m$)

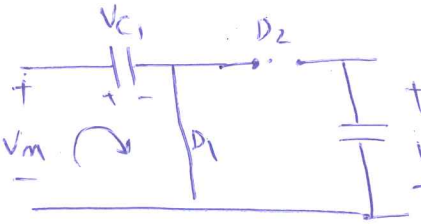
Half wave Voltage doubler



D_1, D_2 are ideal

for ⊕ half signal

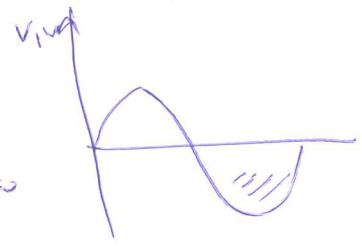


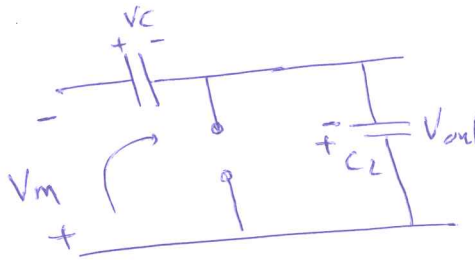


$-V_m + V_{C_1} = 0$

$\Rightarrow \boxed{V_{C_1} = V_m}$

for ⊖ half cycle



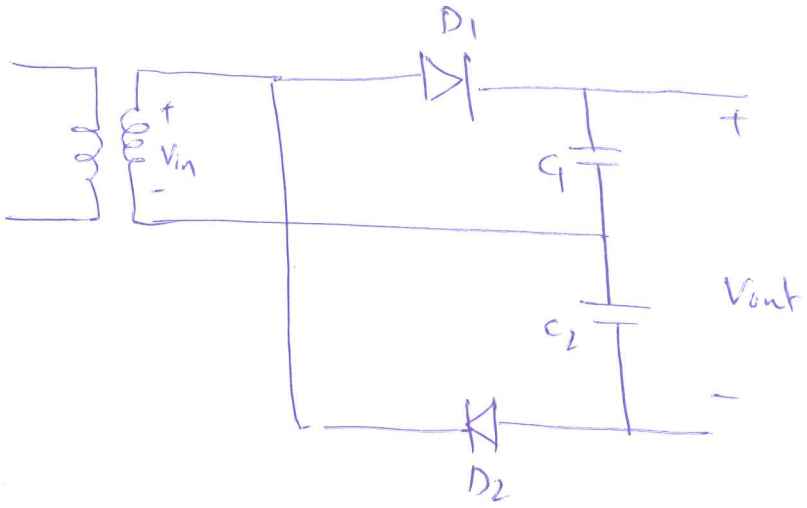


$+V_m + V_C - V_{out} = 0$

$V_m + V_m - V_{out}$

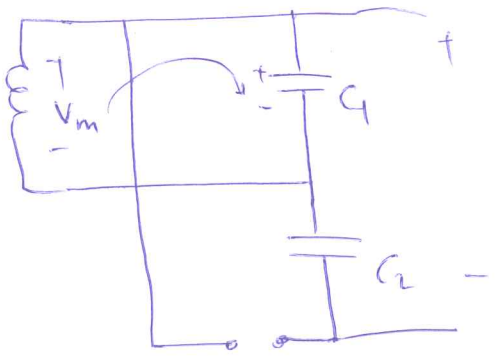
$\Rightarrow V_{C_2} = V_{out} = 2V_m$

Full wave Voltage doubler



C_1 and C_2 are discharge.

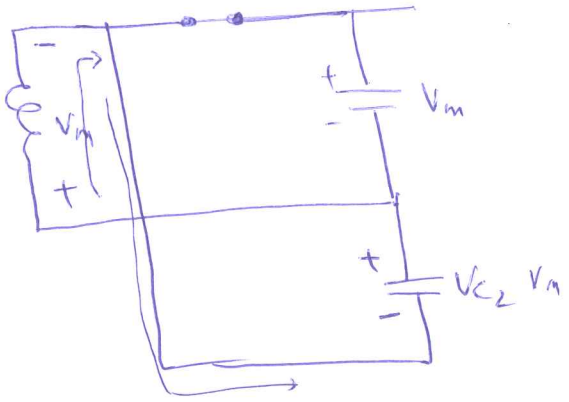
for ⊕ cycle → D_1 is ON (FB), D_2 is OFF (RB)



$V_m - V_{C_1} = 0$

$V_{C_1} = V_m$

for ⊖ cycle

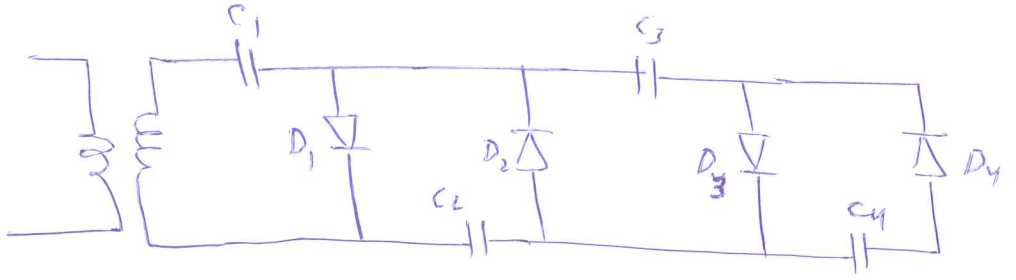


$-V_m + V_{C_2} = 0$

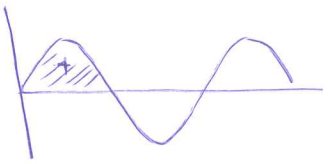
$V_{C_2} = V_m$

$V_{out} = 2V_m$

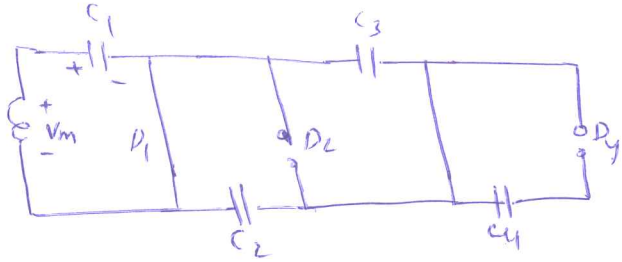
Voltage Multiplier Circuits



For positive half cycle:

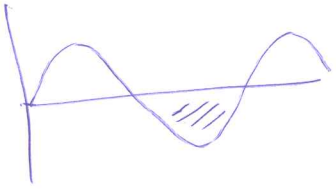


D_1 is FB
D_2 is RB
D_3 → FB
D_4 → RB

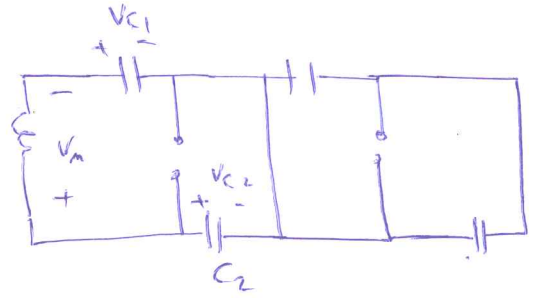


$$+V_m - V_{C_1} = 0 \Rightarrow \boxed{V_{C_1} = V_m}$$

For negative half cycle



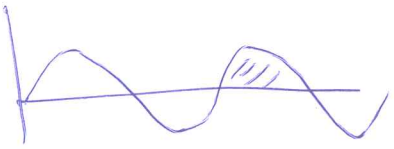
$D_1 \rightarrow$ RB
$D_2 \rightarrow$ FB
$D_3 \rightarrow$ RB
$D_4 \rightarrow$ FB

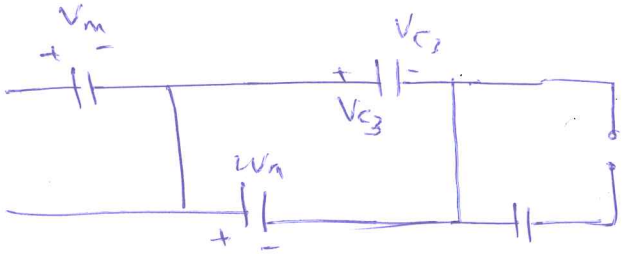


$$-V_m - V_m + V_{C_2} = 0$$

$$\boxed{V_{C_2} = 2V_m}$$

For second positive cycle

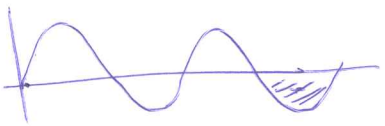




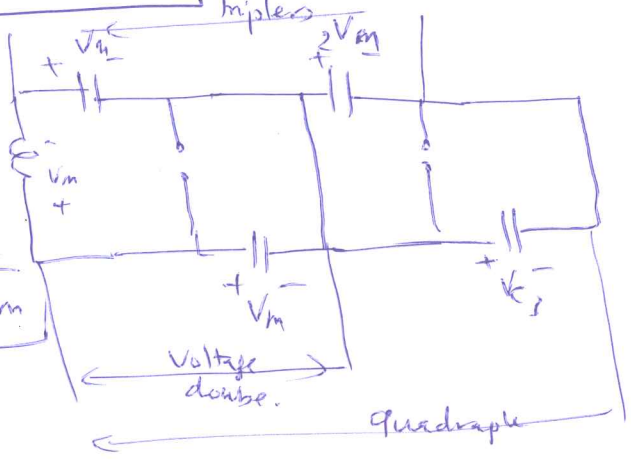
$$+2V_m - V_{C_3} = 0$$

$$\Rightarrow \boxed{V_{C_3} = 2V_m}$$

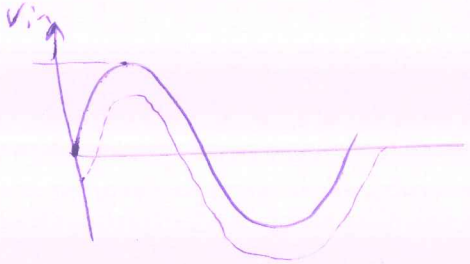
for second positive cycle

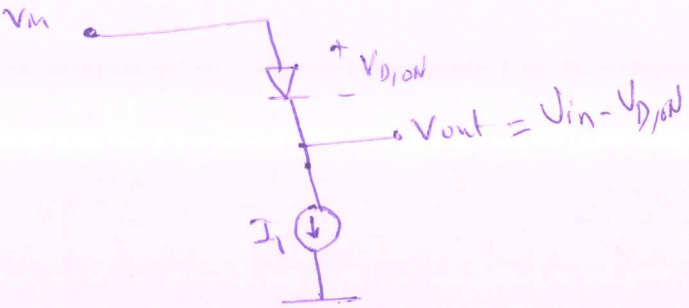


$$-2V_m + V_{C_4} = 0 \Rightarrow \boxed{V_{C_4} = 2V_m}$$



level shift

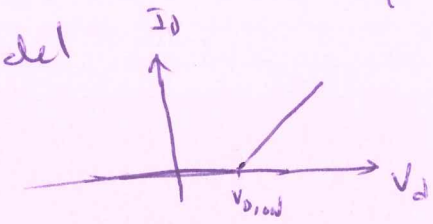




Small Signal Analysis

- Charach of diode
- ~~Price~~ wise Model





$V_d = V_{D,ON} + IR$

$\Rightarrow$ 

$r_d = \frac{V_T}{I_D} = \frac{26mV}{I_D}$

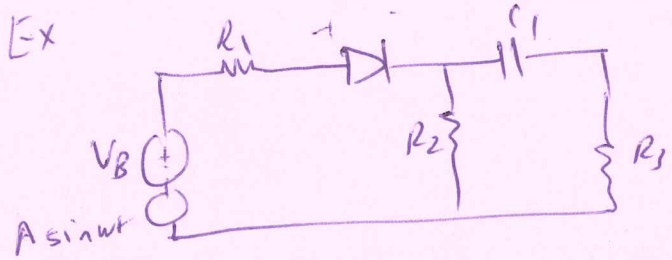
To Solve Problem

1) dc analysis : C $\longrightarrow$ open
D $\longrightarrow$ $V_{D,ON}$ $\Rightarrow$ find I_D.

2) Ac analysis C $\longrightarrow$ short
D $\longrightarrow$ dynamic resistance $r_d = \frac{V_T}{I_D}$

then Complete the solution

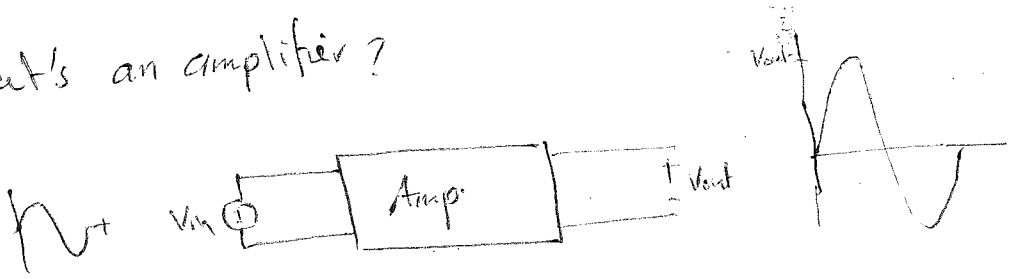
Ex



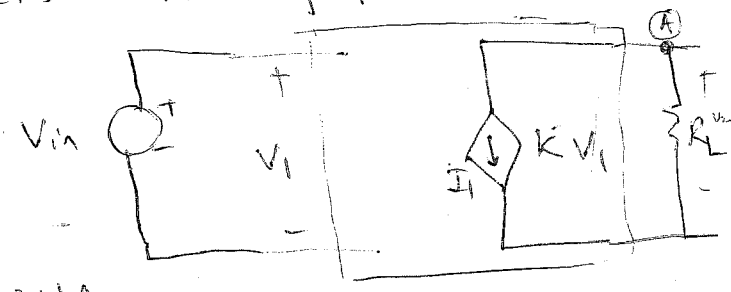
Lect. 14

Today's lect.
- Structure and Symbol of Bipolar Transistor
- Bipolar Transistor operation

- What's an amplifier?



- Let's build amplifier?-



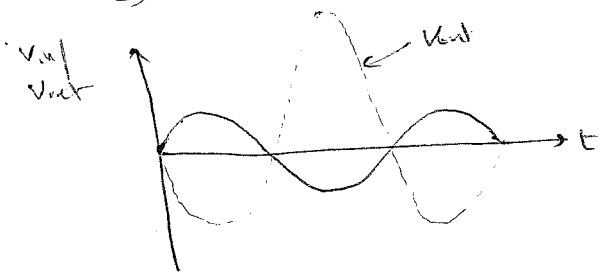
- Voltage dependent current source
- Voltage controlled current source

KCL at point A

$$\frac{V_{out}}{R_L} + kV_1 = 0 \Rightarrow \frac{V_{out}}{R_L} + k V_{in} = 0$$

$$V_{out} = -\underbrace{k R_L}_{-5} V_{in}$$

$$\Rightarrow V_{out} = -5V_{in}$$

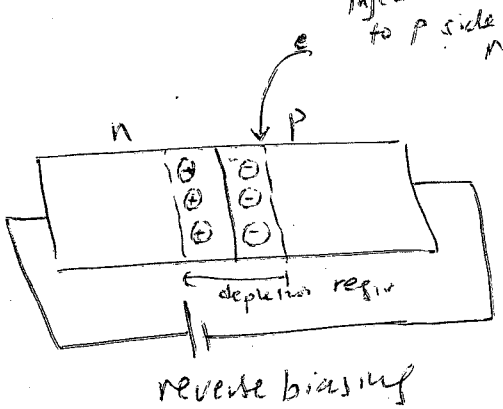


the sign ⊖ is meaning there is phase shift between

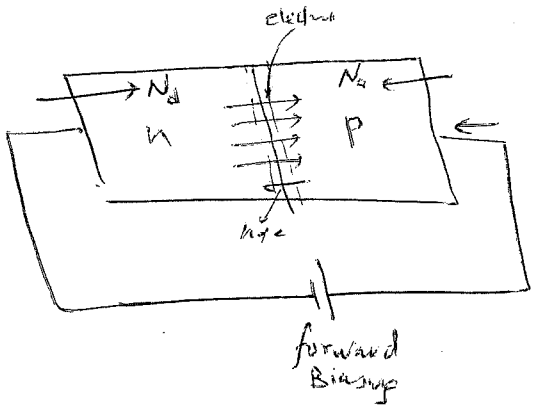
- Structure
- A few observation:
  - Concept of carrier injection:

⇒ so we have create current

x If we injected electron so it is collected by n side



* Effect Asymmetric Doping

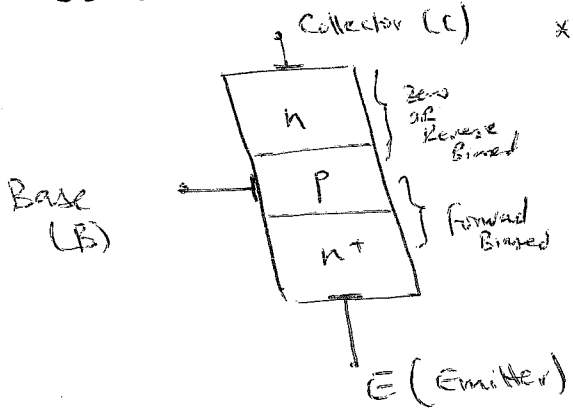


- If we have n-type to doping (N_d)
- P-type Lightly doping (N_a)

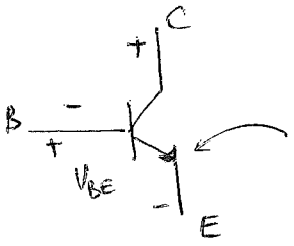
* current of electrons becomes greater than holes.

* Structure and Symbol

- It has three Semiconductor regions.

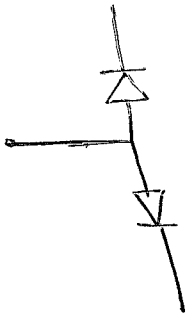


* we have asymmetric doping
n+ : have heavy dopping
n : have lower dopping than n+



B-E junction is Forward Biased
C-B " " Reversed Biased
⇒ Active Forward Bias
Active forward Region

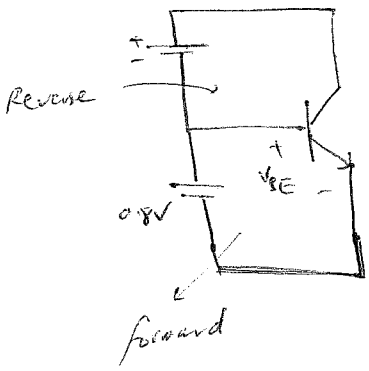
(*) The equivalent but is not work as amplifier



(*) Base Region is very thin.

Operation of Bipolar Transistor

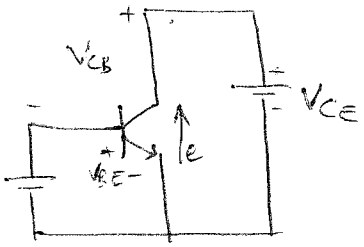
- BE junction have to be forward
- BC " " " " reverse.



⇒ isn't practical Connection.

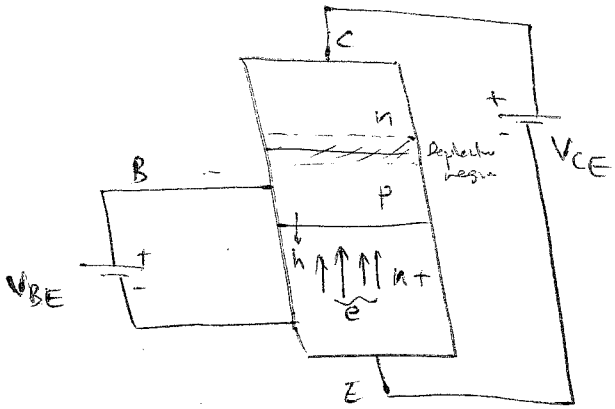
$$V_{CB} = V_{CE} - V_{BE} \geq 0$$

$$\Rightarrow V_{CE} \geq V_{BE} = 0.8V$$



For BE forward Junction

n+: has lots of electron and some hole



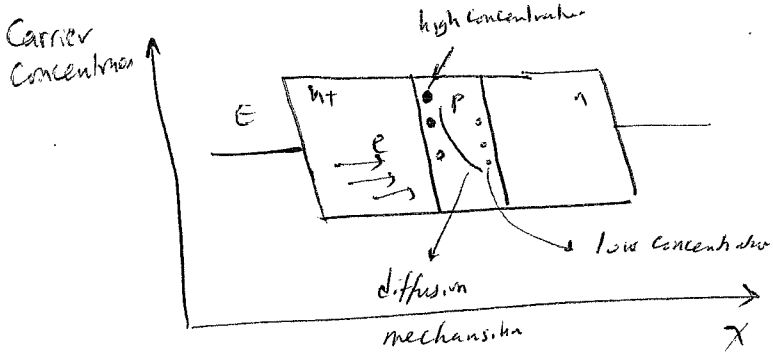
- For BC Reverse Junction that create depletion Region
- since the base is thin that means the electron remain goes toward to C.

and very few of electrons goes to the B path.

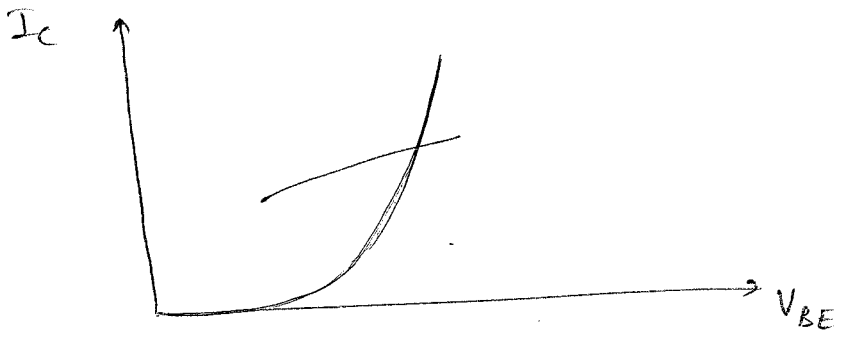
Ⓧ Question By what mechanism electrons flow through the base (drift or diffusion)

Base region is thin and sustains little voltage

⇒ neligible drift current.



- What happen if $V_{BE} \uparrow$, Collector current increases



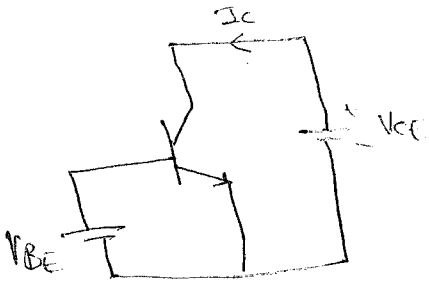
$$I_S = I_S \exp\left(\frac{V_{BE}}{V_T} - 1\right)$$

Lect. 15

Today's Lect.

- Basic properties of Bipolar Transistor
- Terminal currents
- Concept of Bias

* Basic properties of Bipolar Transistor

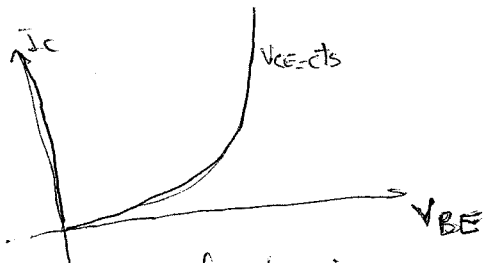


$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T} - 1\right)$$

$$I_S = \frac{A_E}{\text{Emitter Area}} \cdot \frac{q n_i^2 D_n}{W_B N_B}$$

W_B: Base width
N_B: Doping in Ba
D_n: deresity of El

* $I_C = f(V_{BE})$



- How much does I_C change if V_{BE} increases by 60mV the current I_C changes by a factor of 10X
- In most cases $I_C \cong I_S \exp\left(\frac{V_{BE}}{V_T}\right)$

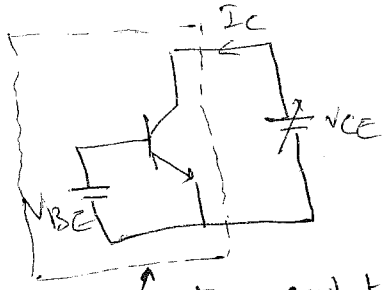
$$\Rightarrow V_{BE} = V_T \ln \frac{I_C}{I_S}$$

Example:
We double the area of a transistor and decrease its base emitter voltage by 60mV. What is the change in the collector current?

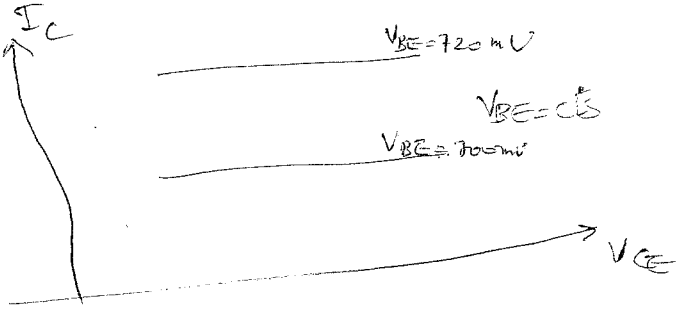
$$I_S \exp\frac{V_{BE}}{V_T} \longrightarrow 2I_S \exp\frac{V_{BE}}{V_T} \underbrace{\exp\frac{-60mV}{V_T}}_{0.1}$$

$$= 0.2 I_S \exp\frac{V_{BE}}{V_T}$$

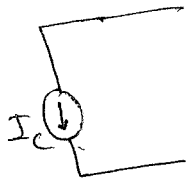
* I_C vs V_{CE}



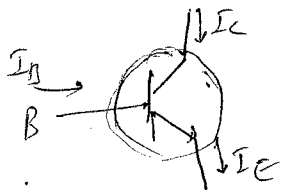
acts as constant current source



* Bipolar Transistor as a voltage dependent current source



* Terminal Currents:



$$I_C = I_S \exp\frac{V_{BE}}{V_T}$$

$I_B \propto I_C$ $\quad I_C = \beta I_B$ $\quad \beta$: 50–200

β: current gain

$$I_B = \frac{I_S}{\beta}\exp\left(\frac{V_{BE}}{V_T}\right)$$

$$I_E = I_C + I_B$$

$$= \frac{\beta+1}{\beta} I_S \exp\frac{V_{BE}}{V_T}$$

Example: A bipolar Transistor has a collector current of 1mA and $I_S = 10^{-16}A$, $\beta = 50$

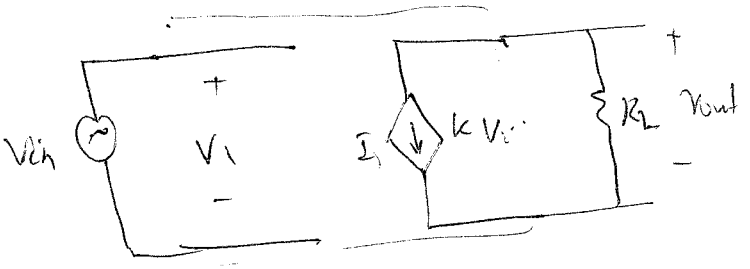
(a) How much is V_{BE}?

$$V_{BE} = V_T \ln \frac{I_C}{I_S} = 778\ mV$$

(b) Calculate I_B

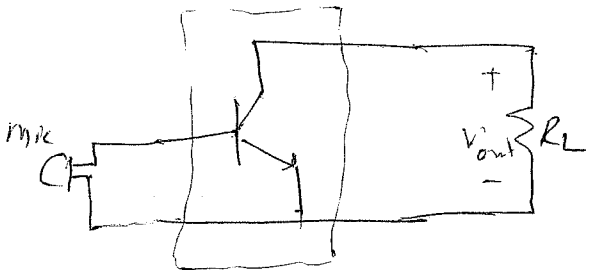
$$I_B = \frac{I_C}{\beta} = \frac{1mV}{50} = 20\mu A$$

* Let's build an amplifier



$V_{out} = -k V_1 R_L$

$A_V = \frac{V_{out}}{V_{in}} = -k R_L$



Lect. 16

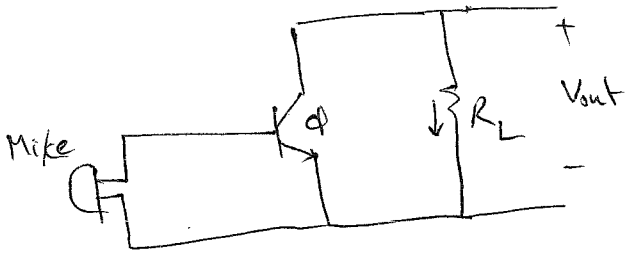
Today's lect.

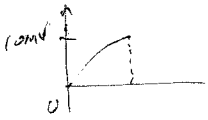
- Simple Amp Revisited
- Concept of Biasing
- Concept of Transconductance

Review:

- Bipolar Transistor charact
- Simple amplifier

* Simple Amp Revisited:





Ex: $I_S = 5\times10^{-16}\,A$

$I_L = \frac{V_{out}}{R_L}$

$I_C = -\frac{V_{out}}{R_L}$, $V_{out} = -R_L I_C$

$V_{out} = -R_L I_S \left[\exp\left(\frac{V_{BE}}{V_T} - 1\right)\right]$

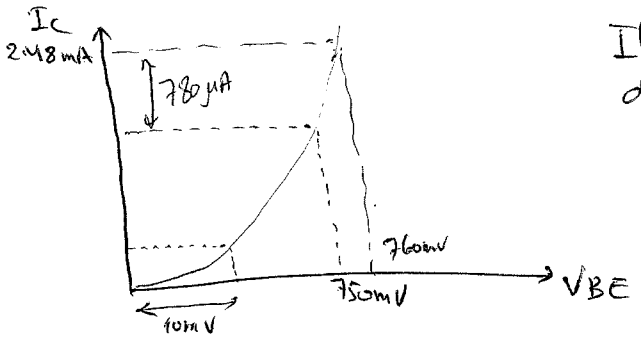
$V_{BE} = 10mV \Rightarrow V_{out} = -R_L \times 5\times10^{-16}\left[\exp\left(\frac{10}{26} - 1\right)\right]$

$= -R_L \underbrace{(2.35\times10^{-16})}_{I_C}\ V$

If Vout should be $= -100mV$

$\Rightarrow R_L = 4.25\times10^{16}\,\Omega$ (not practical)

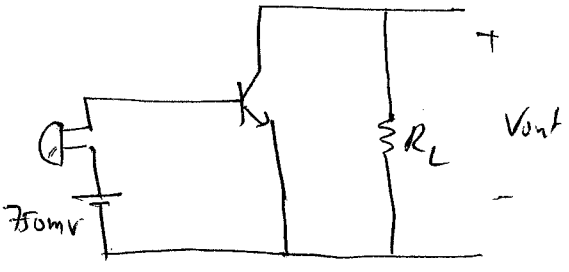
So we conclude that this circuit doesn't work as amplifier.
So inorder to fix it:



When $V_{BE} = 750mV$

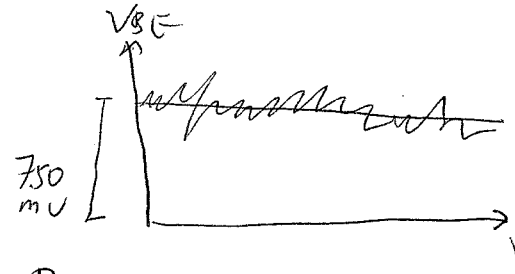
$\Rightarrow I_C = 1.7mA$

If we don't apply the mike signal direct.
So let us add a battery as:



If Mike generate 10mV → V_{BE} becomes 760mA

$R_L = \frac{100mV}{730\mu A} \cong 128\,\Omega$



in the absence of signal.

* Biasing : Provide proper voltage and current so that the transistor can amplify.

(*) Operating point : the bias values chosen for $V_{BE}, I_C, \ldots\ldots$

example $V_{BE} = 750mV$

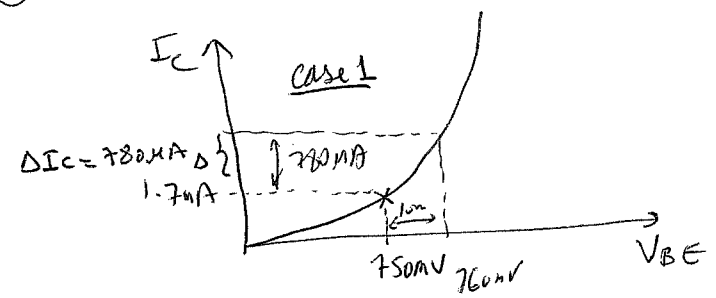
$I_C = 1.7mA$

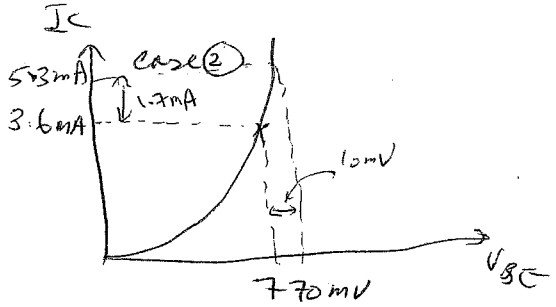
(*) Observations :

(1) A bipolar Transistor can acts as voltage dependent current source $\Rightarrow$ its collector current changes in response to its base-Emitter voltage.

(2) The operating point determines how the transistor responds responds.

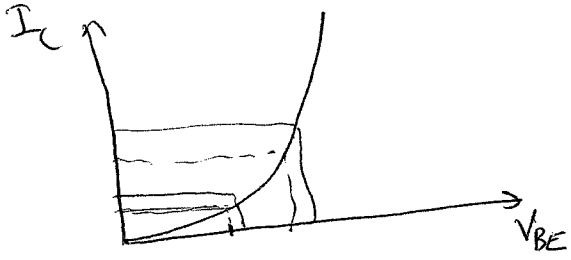
(3) Which operating point is better?





- We see case 2 is better

Concept of Transconductance :



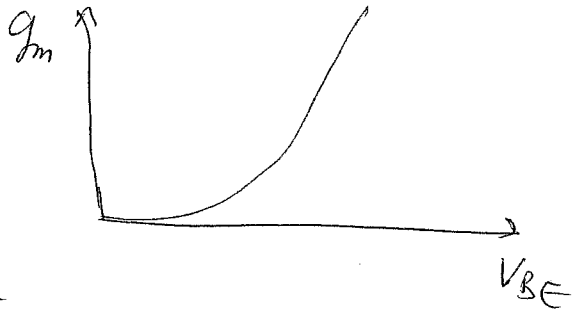
$$g_m = \frac{d I_C}{d V_{BE}}$$: transconductance

Ex for case 1 : $g_{m1} \simeq \frac{780\mu A}{10mV} = 0.078$ Siemens (S)

for case 2 $g_{m2} \simeq \frac{1.17mA}{10mV} = 0.17\,S$

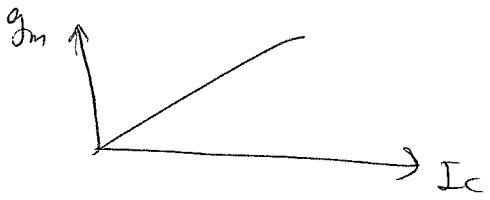
$$g_m = \frac{d}{dV_{BE}}\left[I_S \exp\left(\frac{V_{BE}}{V_T}\right)\right]$$

$$\boxed{g_m = \frac{I_S}{V_T}\exp\left(\frac{V_{BE}}{V_T}\right)}$$



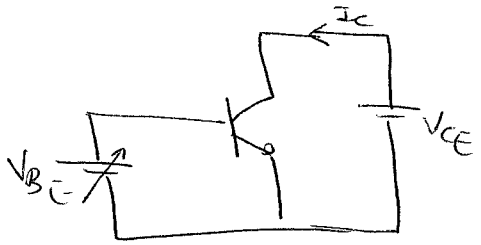
$$g_m = \frac{1}{V_T}\left\{ I_S \exp\frac{V_{BE}}{V_T}\right\} = \frac{I_c}{V_T}$$

$$\boxed{g_m = \frac{I_c}{V_T}}$$



If $I_c = 1mA \Rightarrow g_m = \frac{1mA}{\frac{26mV}{25}} \simeq \frac{1}{25\Omega} = 0.04\,S$

* With no bias, $I_c = 0$, $g_m = 0 \Rightarrow$ no amplification.
* For amplification, need certain g_m, $\Rightarrow$ certain I_c
  $\Rightarrow$ certain V_{BE}
* Trade off between g_m and Power consumption.
* A small change in $V_{BE} \equiv$ small fraction of V_T
* <u>For g_m Calculation</u>



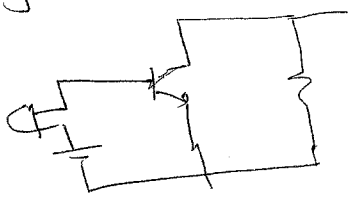
during g_m measurment V_{CE} must be constant

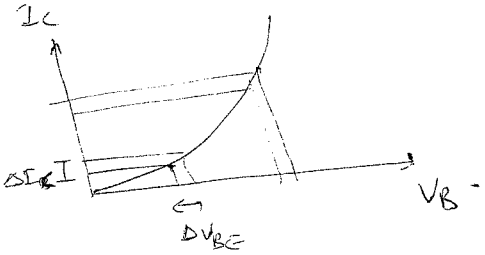
lect. 17

Today's lect.
- I-V Characteristic of Bipolar Transistor
- Small Transistor Model
- Large ~~Small~~ Signal and Small Signal Model (operation)

Review:

- Biasing:

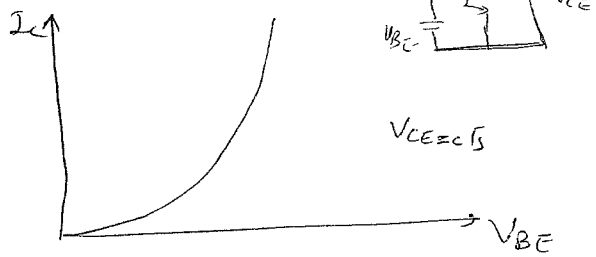


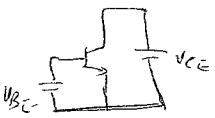


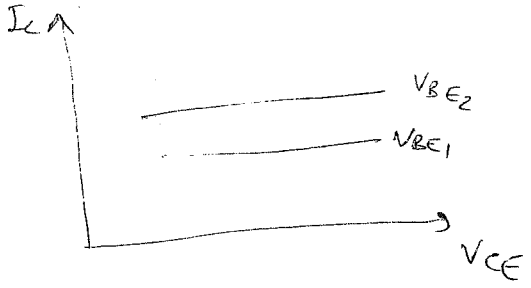
- Transconductance

$$g_m = \left.\frac{dI_C}{dV_{BE}}\right|_{V_{CE}=cts} \qquad g_m = \frac{I_C}{V_T}$$

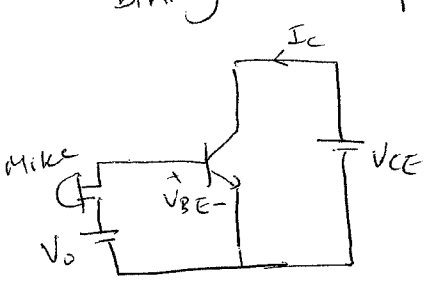
* I-V Characteristics

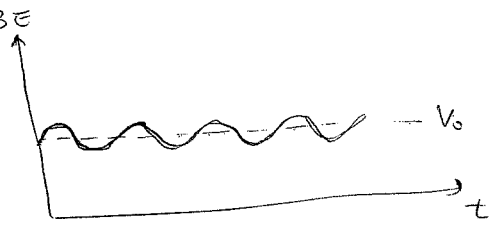


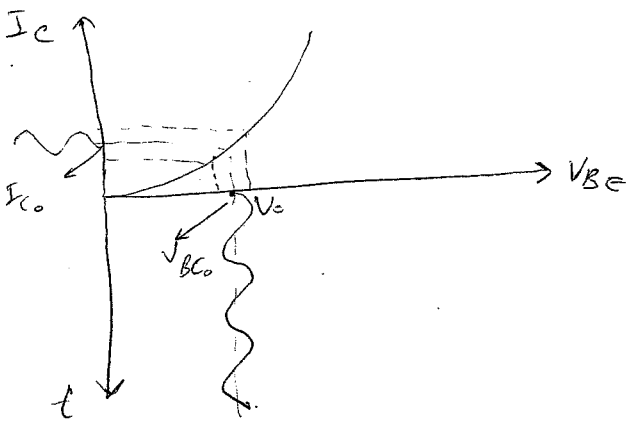


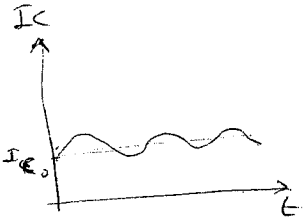


* Combining Time Response with I, V characteristics

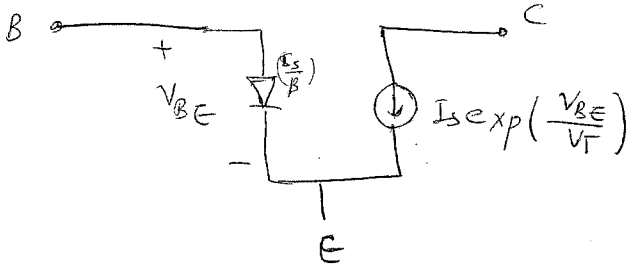






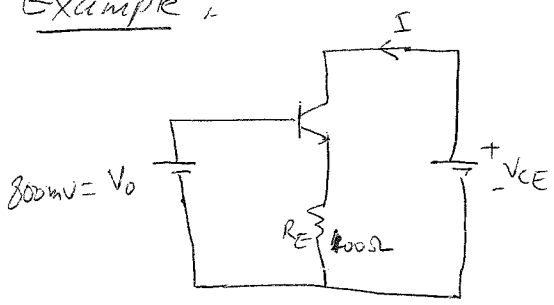


* Simple Bipolar Transistor Model (in forward active region)



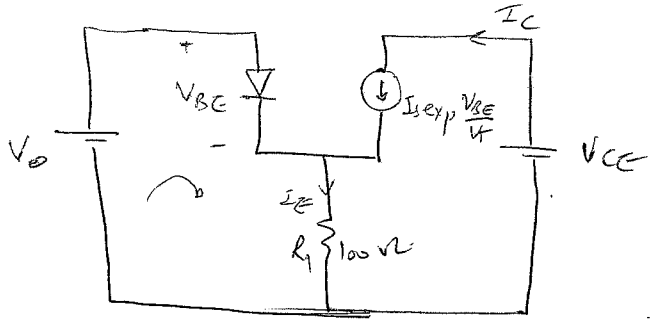
$$I_B = \frac{I_C}{\beta} = \frac{I_S}{\beta} \exp \frac{V_{BE}}{V_T}$$

Example :



$I_S = 5 \times 10^{-16} A$

Calculate I_c



$I_E \cong I_C$

KVL: (input side) $V_0 = V_{BE} + R_1 I_E = V_{BE} + R_1 I_C$

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \Rightarrow V_{BE} = V_T \ln \frac{I_C}{I_S}$$

$$\Rightarrow V_0 = V_T \ln \frac{I_C}{I_S} + R_1 I_C \quad \text{(non linear equation)}$$

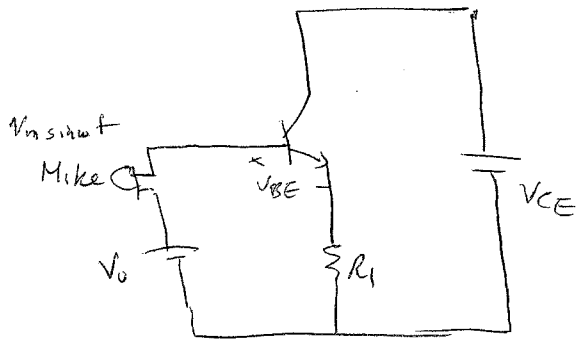
$$V_0 - R_1 I_C = V_T \ln \frac{I_C}{I_S} \quad \text{(Make a guess to find } I_C\text{)}$$

Guess $I_C = 1mA$

Because of non-linearity equation

$\Rightarrow$ Solution is more complex.

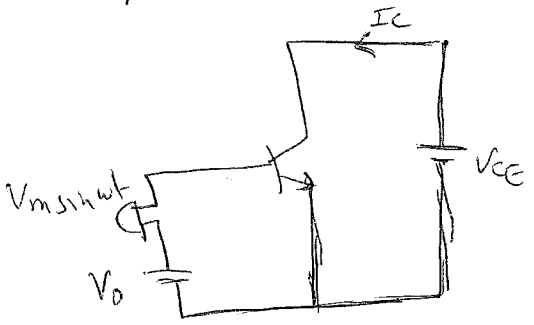
Example:



$$V_0 + V_m \sin\omega t - R_1 I_c = V_T \ln \frac{I_c}{I_s}$$

Is more complicate.

Example:



$$V_{BE} = V_0 + V_m \sin\omega t$$

$$I_c = I_s \exp\left(\frac{V_0 + V_m \sin\omega t}{V_T}\right)$$

Large Signal Operation

The signal is arbitrary large.

Small Signal Operation.

The signal applied is very small.

$$I_c = I_s \exp\frac{V_0}{V_T} \exp\frac{V_m \sin\omega t}{V_T}$$

Math $e^{\varepsilon} \cong 1+\varepsilon \quad \varepsilon \ll 1$

assume $V_m \ll V_T$

$$I_c = I_s \exp\frac{V_0}{V_T}\left[1 + \frac{V_m \sin\omega t}{V_T}\right]$$

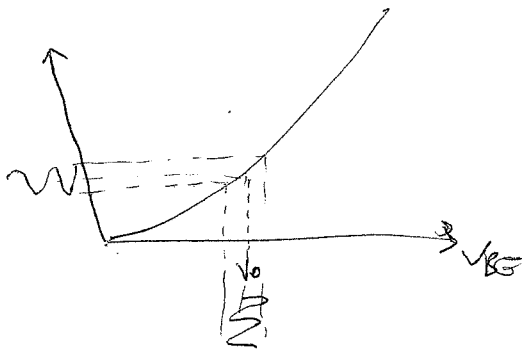
$$= I_s \exp\frac{V_0}{V_T} + \frac{V_0}{V_T}\exp\frac{V_m \sin\omega t}{V_T} \quad I_s \exp\frac{V_0}{V_T}$$

$$= I_{C0} + \frac{I_{C0}}{V_T} V_m \sin\omega t$$

I_{C0} ⇓ biasing current

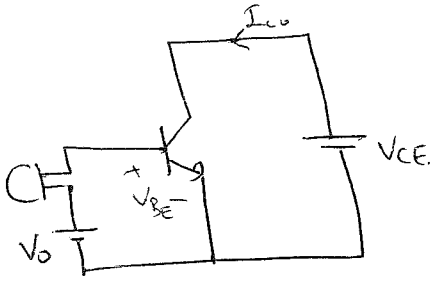
In small signal operation:

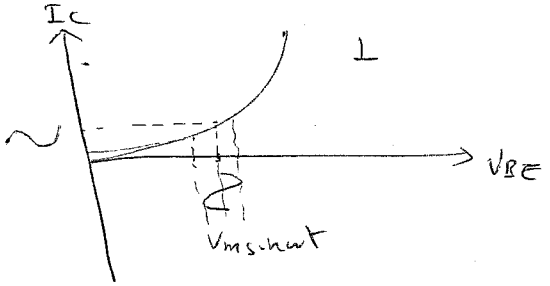
* I_c varies sinusoidally
* $I_c \cong I_{C0} + g_m V_m \sin\omega t$



Today's lect.
- Small Signal Model of Bipolar Transistor
- Early Effect
- Complete Small Signal Model

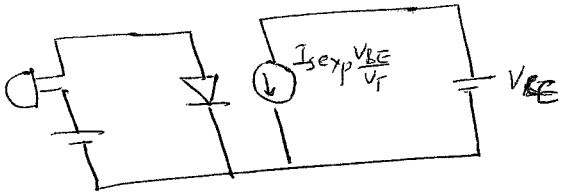
Review
- Large Signal and small Signal operation



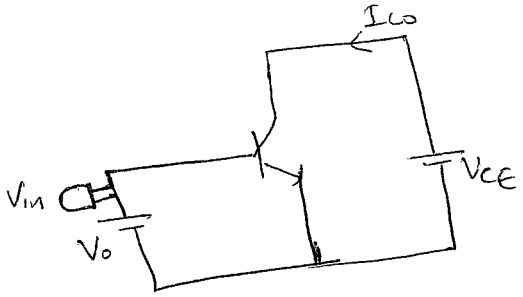


$I_C = I_{CO} + g_m V_m \sin\omega t$

Formal factor



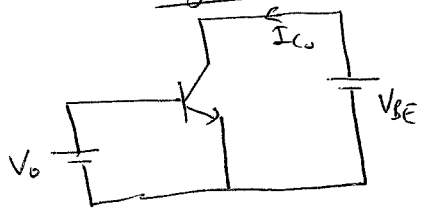
* Small Signal Model



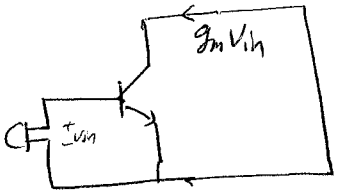
$I_C = I_{CO} + g_m V_{in}$

Using Super-position theorem.

dc analysis (Large Signal Model)

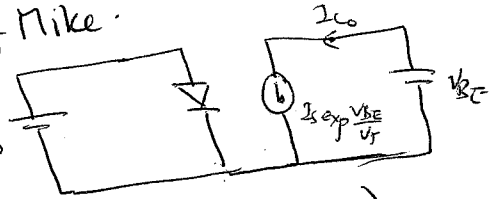


+ AC analysis

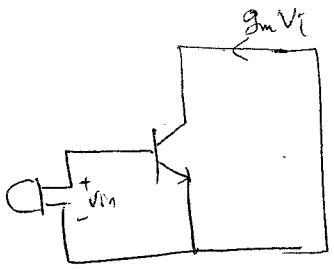


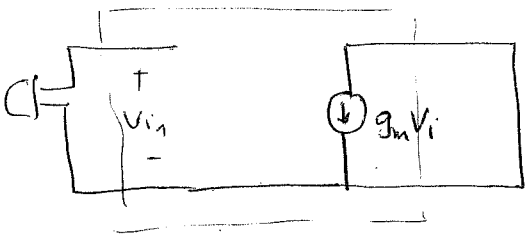
Consider the circuit as two circuit
- Biasing circuit (without the signal of Mike)
- The circuit with Signal of Mike.

Large Signal Model



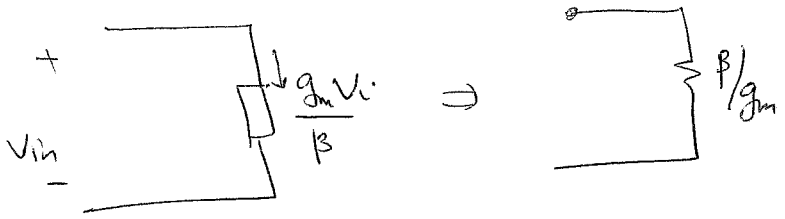
$I_{CO} = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$



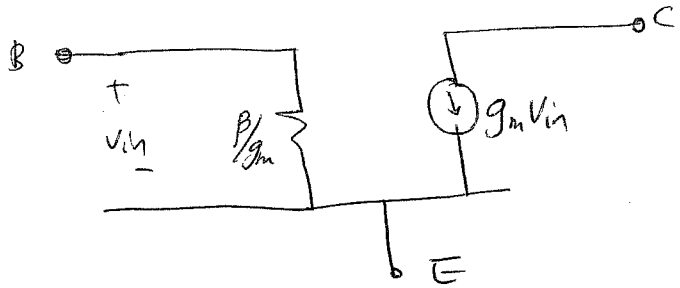


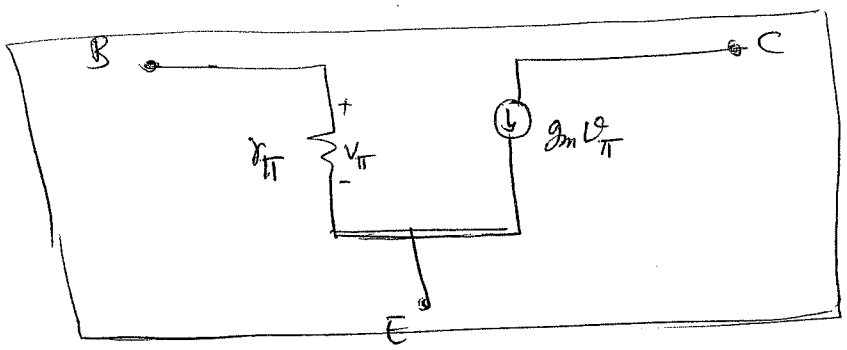
Small Signal Model

$$I_B = \frac{I_C}{\beta} = \underbrace{\frac{I_{CO}}{\beta}}_{\text{dc Biasing}} + \underbrace{\frac{g_m V_i}{\beta}}_{\text{AC}}$$



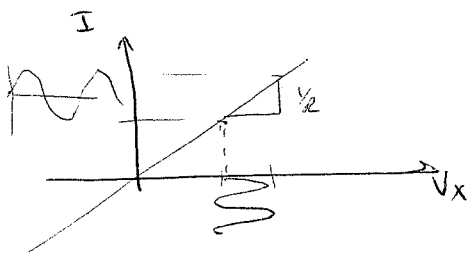
More Complete Small Signal Model

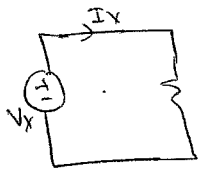




Example

Find the Small Signal Mode of a linear resistor





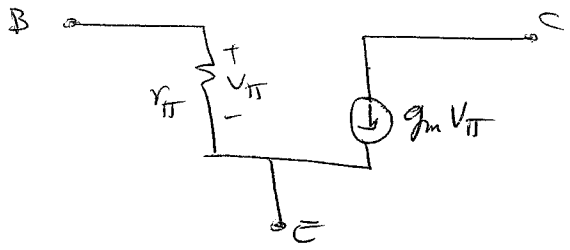
$$I_x = \frac{V_x}{R_1}$$

$$\Delta I_x = \frac{\Delta V}{R_1}$$

has the same model for large and small model

$$g_m = \frac{I_C}{V_T}$$

$$r_\pi = \beta / g_m$$

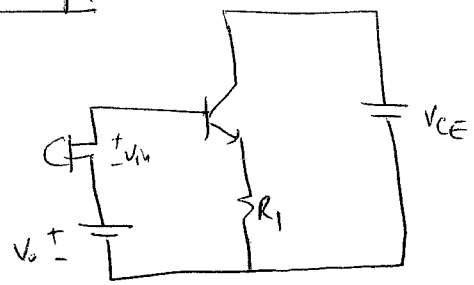


To find the small parameteres, we must first calculate the bias condition

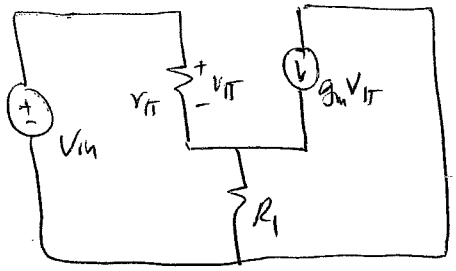
Question: what happens to batteries in small signal operation or analysis?

- Replace All of constant voltage source ⟶ shorted (set to zero)
- Replace All of constant current source ⟶ open (set to zero)

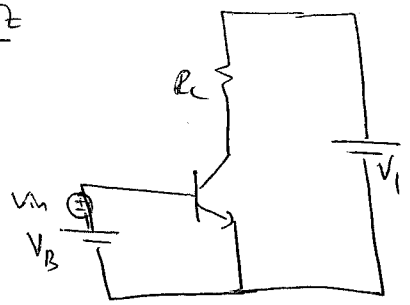
Example:-

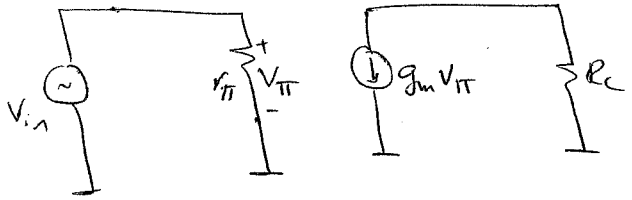


Construct the Small Signal Model



Quiz





* Notation:
  - Large signal quantities are represented by upper Latter
    V_{BE}, I_C, V_{CE}, I_B
  - Small Signal quantites are represented by lower case
    v_{in}, i_c, v_{ce}, v_{BE}

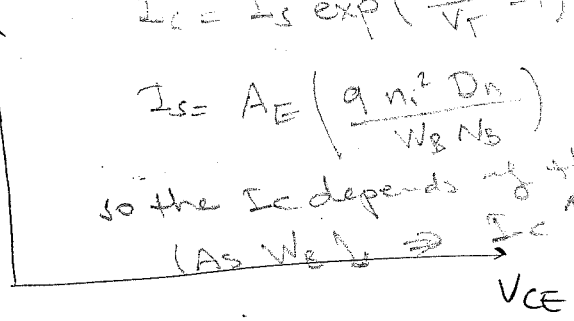
Early Effect :

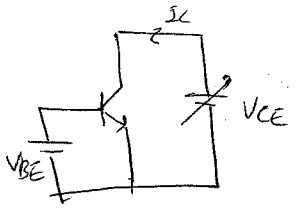
$$I_c = I_S \exp\left(\frac{V_{BE}}{V_T} - 1\right)$$

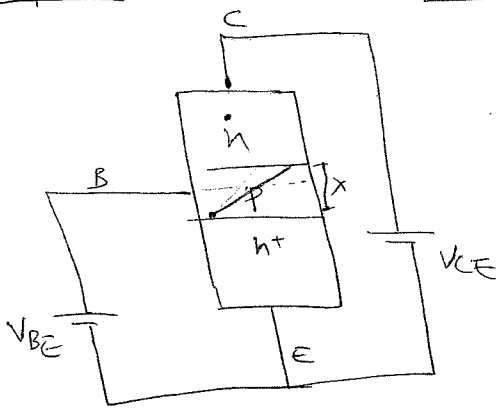
$$I_S = A_E \left(\frac{q\, n_i^2\, D_n}{W_B\, N_B}\right)$$

so the I_c depends on the width of Base (W_B)

(As $W_B \downarrow \Rightarrow I_c \uparrow$)

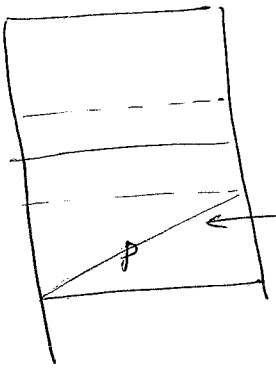


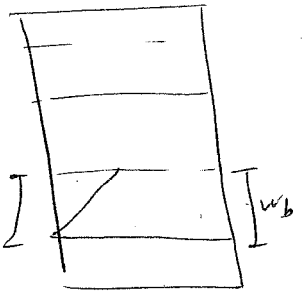




Since V_{CB} junction is reverse
so the depletion region becomes wider

As V_{CE} goes up, the width of Base decrease





$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

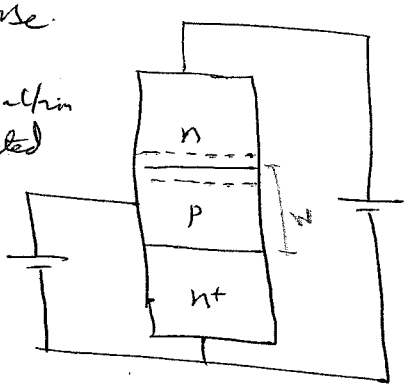
$$= I_S \exp\left(\frac{V_{BE}}{V_T}\right)\left(1 + \frac{V_{CE}}{V_A}\right) \leftarrow \text{large signal Model}$$

V_A: early voltage

- We have two PN junction
  - BE junction is forward
  - CB junction is Reverse.

- For Applying Reverse Bias on CB junction
  ⇒ depletion Region is created

- As V_{CE} increasing ⇒ Depletion Region is increased and the W_B (base width decrease)



$$I_{c_1} = I_S \exp\left(\frac{V_{BE}}{V_S} - 1\right)$$

$$I_S = \frac{A_E\, q\, D_n\, n_i^2}{N_E\, W_B}$$

as W_B decrease
⇒ I_c is increase

⇒

$$\boxed{I_c = I_S \exp \frac{V_{BE}}{V_T}\left[1 + \frac{V_{CE}}{V_A}\right]}$$

V_A: Early Voltage

اقلب الصفحة

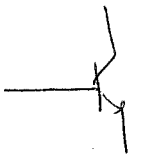
lect. 18

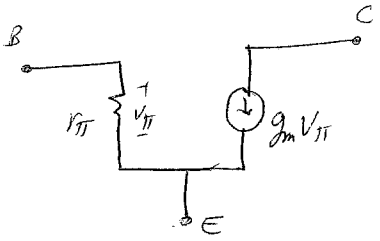
Today's lect.

- Inclusion of Early Effect in Small Signal Model
- PNP Transistor

Review:

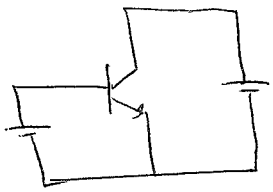
- Small Signal Model



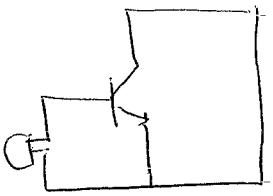


- $r_\pi = \frac{\beta}{g_m}$
- $g_m = \frac{I_C}{V_T}$

- Analyze and Design in 2 phase



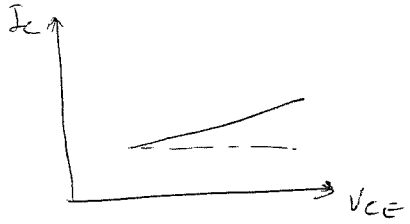
Bias



Signal

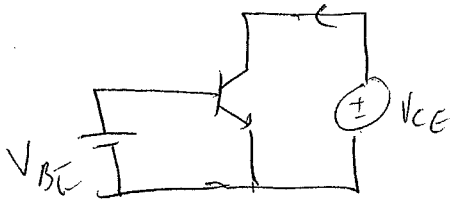
- Early Effect

$$I_C = I_S \exp\frac{V_{BE}}{V_T}\left(1+\frac{V_{CE}}{V_A}\right)$$



- Incorrect view of large Signal and Small Signal Models
  - Large Signal Model : DC analysis (large signal model)
  - Small Signal Model : AC analysis (Small Signal Model)

- Early Effect





$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)\left(1+\frac{V_{CE}}{V_A}\right)$$

- Official Model of Small Signal model dervation
  - step 1 : Assume the transistor is baised at a certain operating point.
  - step 2 : Apply a voltage change between two thermanals and measure the resulting current changes.

• steps: Model the current changes by proper electric devices

- g_m: $g_m = \frac{dI_C}{dV_{BE}}$

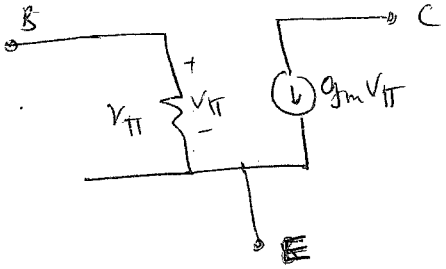
$$= \frac{d}{dV_{BE}} \left(I_S \exp \frac{V_{BE}}{V_T} \left(1 + \frac{V_{CE}}{V_A}\right)\right)$$

$$= \frac{I_S}{V_T} \exp \frac{V_{BE}}{V_T} \left(1 + \frac{V_{CE}}{V_A}\right)$$

$$\boxed{g_m = \frac{I_C}{V_T}}$$

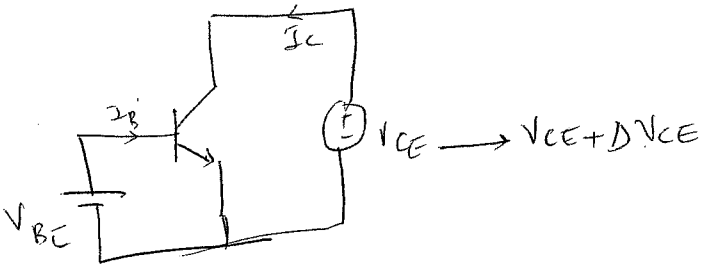
- r_π: $I_B = \frac{I_C}{\beta} \Rightarrow \quad \Delta I_B = \frac{\Delta I_C}{\beta} \Rightarrow \quad r_\pi = \beta / g_m$

Is this model correct?



$\Rightarrow$ No,

* Inclusion of Early Effect.



$$I_C + \Delta I_C = I_S \exp \frac{V_{BE}}{V_T} \left(1 + \frac{V_{CE} + \Delta V_{CE}}{V_A}\right)$$

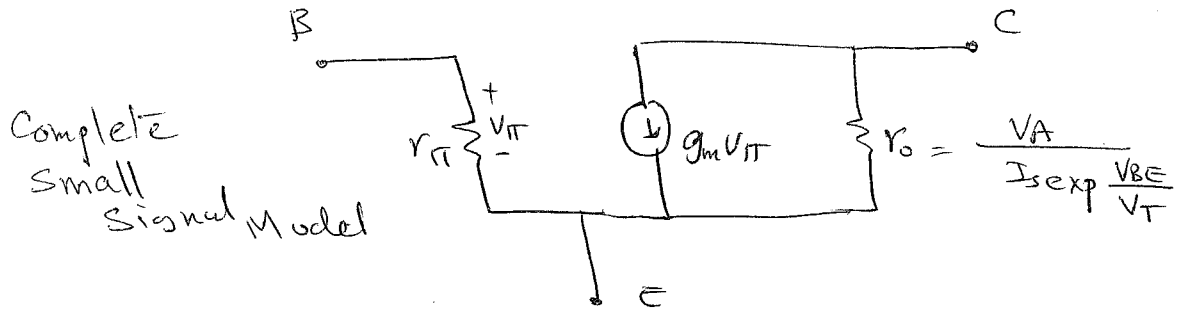
$$= I_S \exp \frac{V_{BE}}{V_T} \left(1 + \frac{V_{CE}}{A}\right) + I_S \exp \frac{V_{BE}}{V_T} \left(\frac{\Delta V_{CE}}{V_A}\right)$$

$$= I_C + \Delta I_C$$

$$\Delta I_C = I_S \exp \frac{V_{BE}}{V_T} \left(\frac{\Delta V_{CE}}{V_A}\right)$$

we see that $\Delta V_{CE} \longrightarrow$ linear variation in ΔI_C

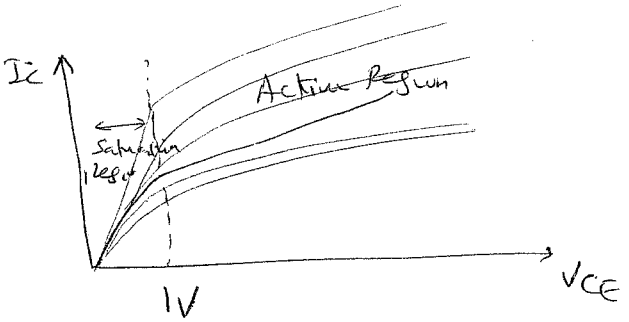
The small signal Model becomes



Complete Small Signal Model

for $r_o \leq \frac{V_A}{I_C}$

- Note:-

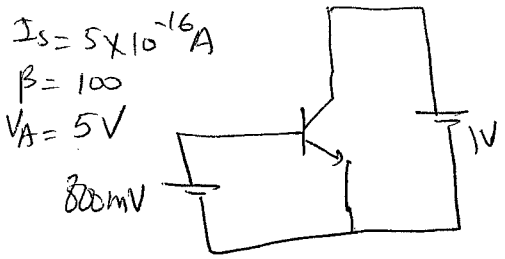


- Saturation must be avoided
- Saturation can be obtained when the two pn junctions are forward.
- To avoid Saturation:

If $V_{BE} = 800mV$, $V_{CE} \geq 800mV$

- Soft saturation when $0.5V \leq V_{CE} \leq 0.8V$

Example,

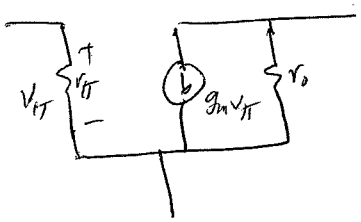


Find the small signal model

- $I_C = I_S \exp \frac{V_{BE}}{V_T} \left(1 + \frac{V_{CE}}{V_A}\right)$

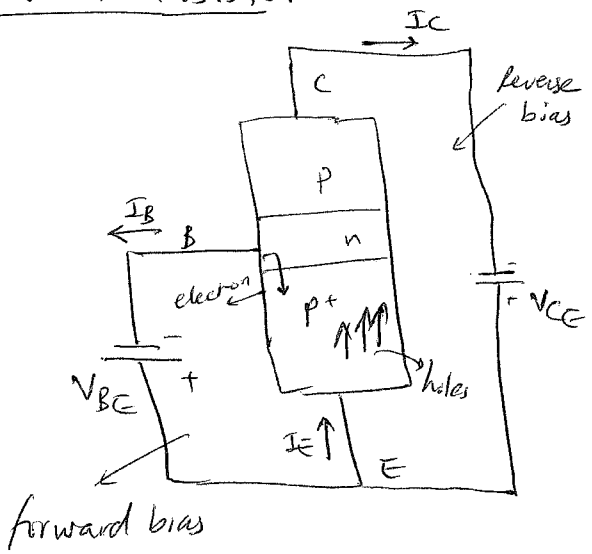
  $I_C = 13.8mA$

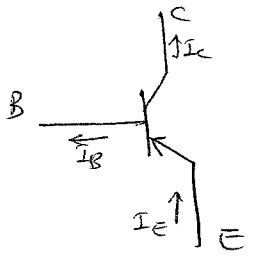
- $g_m = \frac{I_C}{V_T} = 0.53 S = \frac{1}{1.9 \Omega}$
- $r_\pi = \beta / g_m = 1900 \Omega$
- $r_o = \frac{V_A}{I_C} = 362 \Omega$



- Note: $g_m r_o \gg 1$ when will see this note is very important.

PNP Transistor

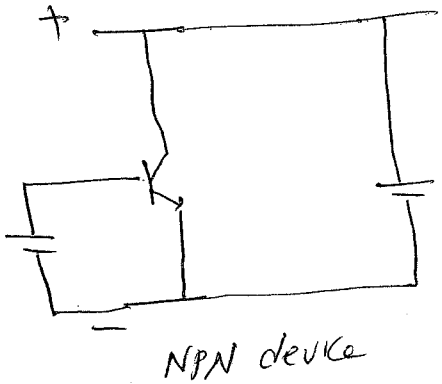


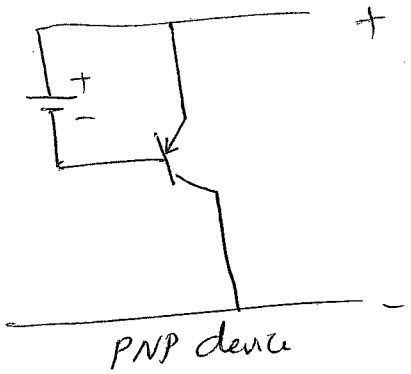


Forward Active Region:

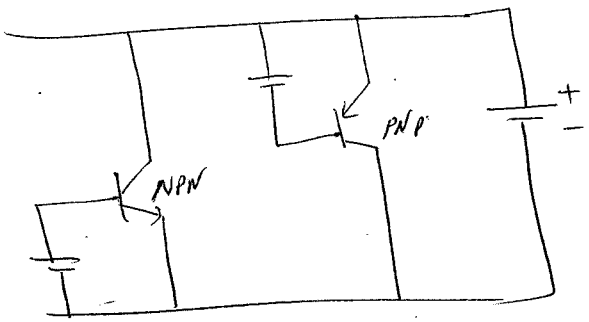
1) $V_{EB} > 0$
2) $V_{EC} \leqslant V_{EB}$

Conventional we use

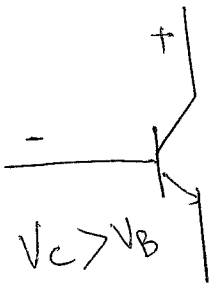




Visualization



Visualization



Active



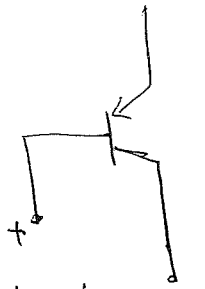
$V_C = V_B$

Edge of Saturation



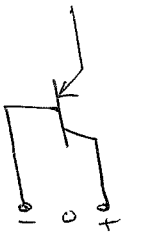
$V_B > V_C$

Saturation

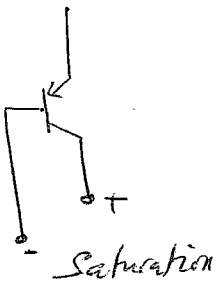


$V_C < V_B$

Active

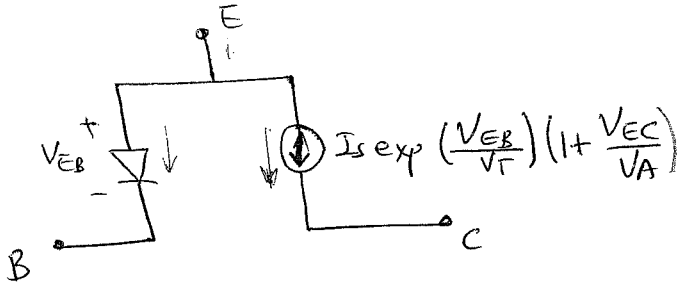


Edge of Saturation



Saturation

- Large Signal Model of PNP device.

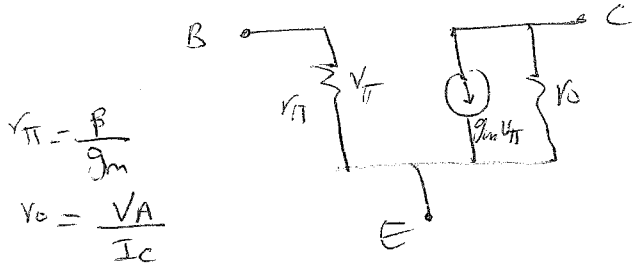


lect. 19

Today's lect.
- Small Signal Model of PNP Transistor
- Introduction to Amplifiers
- Common Emitter Topology

Review

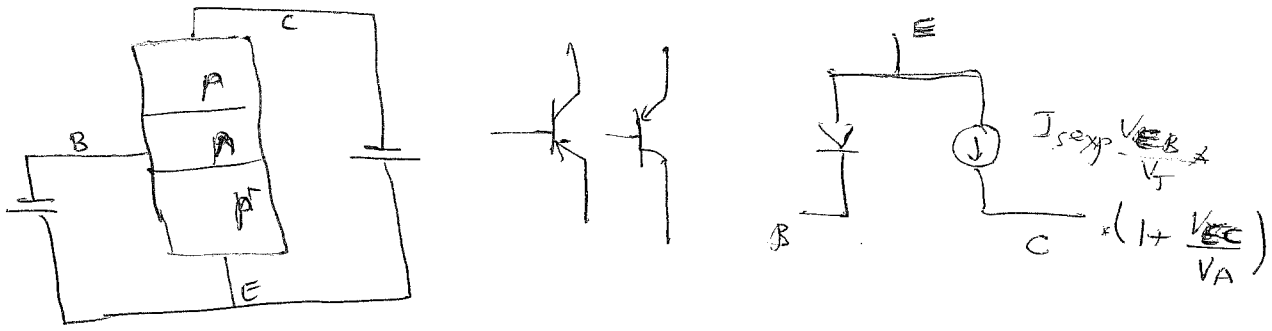
- Inclusion of Early Effect



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

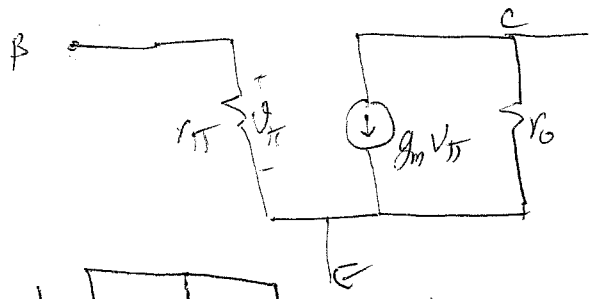
$r_o = \frac{V_A}{I_C}$

- PNP Transistor

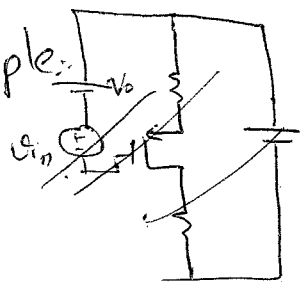


* Small Signal Model of PNP Transistor

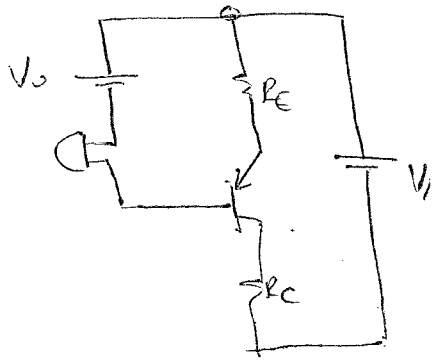
- Identical to small signal model of npn transistor.

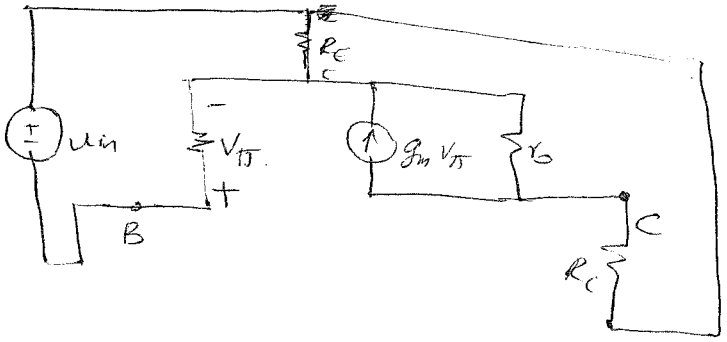


Example:

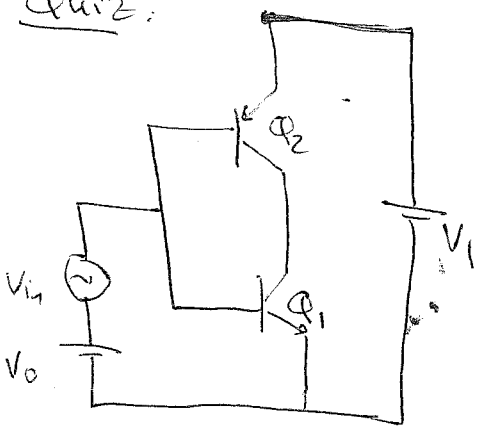


Example Draw the small signal equivalent circuit

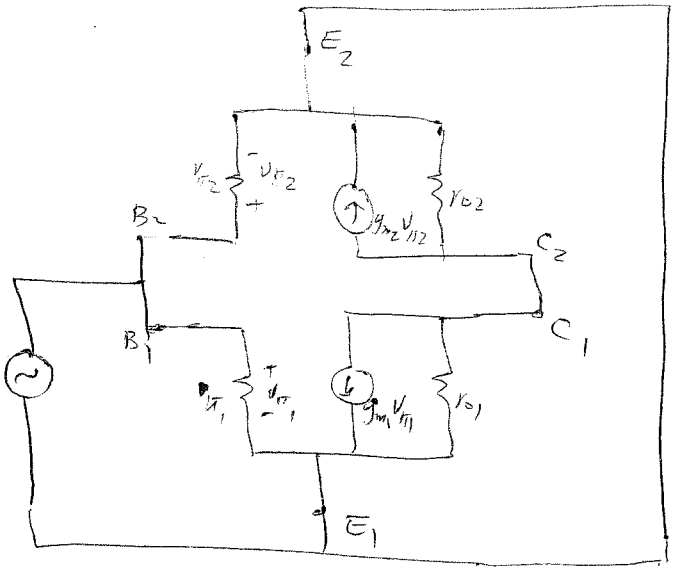




Quiz:



Draw the small signal



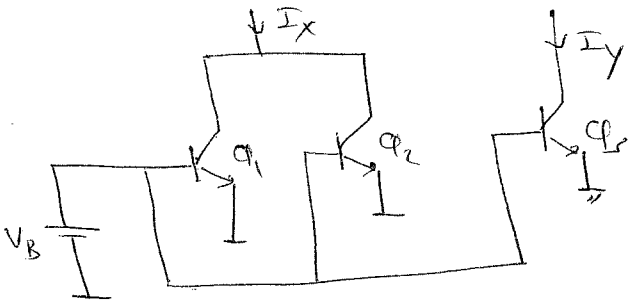
Observation :-

- $r_{o1} \parallel r_{o2}$
- $r_{\pi 1} \parallel r_{\pi 2}$
- $V_{\pi 1} = V_{\pi 2}$
- $g_{m1} V_{\pi 1} \parallel g_{m2} V_{\pi 2}$ so we can adding to be one sour

4.5 $I_{S_1} = I_{S_2} = 3\times10^{-16}\ A$

a) Calculate V_B such that $I_X = 1mA$

b) Choose I_{S_3} such that $I_Y = 2.5mA$



a) $I_{S_1} = I_{S_2} = I_S = 3\times10^{-16}\ A$

$$I_{C_1} = I_{S_1}\exp\frac{V_{BE}}{V_T} = I_{S_2}\exp\frac{V_{BE_2}}{V_T} = I_{C_2} = \frac{I_X}{2} = 0.5\,mA$$

$$I_{C_1} = I_{C_2} = I_S\exp\frac{V_{BE}}{V_T} = 0.5\,mA$$

$$\exp\frac{V_{BE}}{V_T} = \frac{0.5\,mA}{3\times10^{-16}A} = \frac{0.5\times10^{-3}}{3\times10^{-13}} = 0.166\times10^{10}\ A$$

$V_{BE} = V_T \ln\frac{I_C}{I_S}$

$I_{C_1} = I_{C_2} = \frac{I_X}{2}$

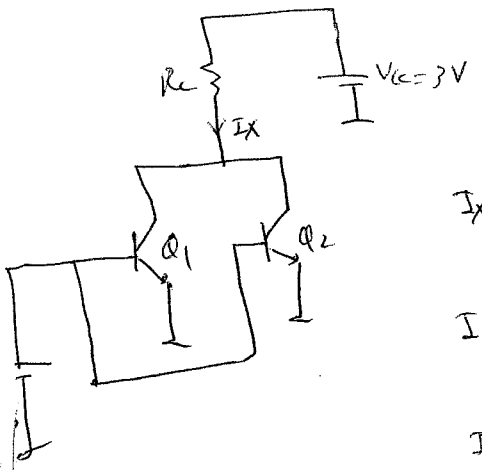
$$V_{BE} = V_T \ln 0.166\times10^{10}$$

$$= 26\times10^{-3}\ln 0.166\times10^{10} = 0.55\,V$$

$$V_{BE} = V_B - V_E = V_B = \boxed{0.55\,V}$$

b) $$I_Y = I_{S_3}\exp\left(\frac{V_{BE_3}}{V_T}\right) \Rightarrow I_{S_3} = \frac{I_Y}{\exp\left(\frac{0.55}{0.026}\right)} = \frac{2.5\times10^{-3}}{e^{\frac{0.55}{0.026}}} = 1.6\times10^{-12}\,A$$

EX 4.6



$V_B = 0.6V$
$I_X = 3.5mA$
$I_{S_1} = 2I_{S_2}$

a) Find I_{S_1}, I_{S_2}

b) Find R_c which replace Q_1, Q_2 at the edge of active mode.

$$I_X = I_{C_1} + I_{C_2}$$

$$= I_{S_1}\exp\frac{V_{BE}}{V_T} + I_{S_2}\exp\frac{V_{BE}}{V_T} = 3I_{S_2}\exp\frac{V_{BE}}{V_T}$$

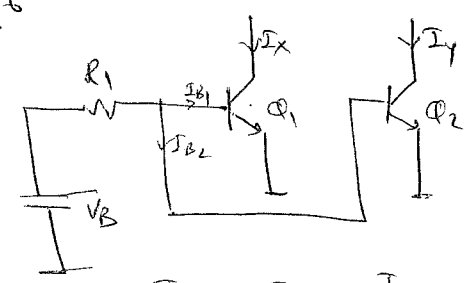
$$I_{S_2} = \frac{I_X}{3\exp\frac{V_{BE}}{V_T}} = \frac{3.5\times10^{-3}}{3\exp\left(\frac{0.6}{0.026}\right)} = 2.217\times10^{-13}\,A$$

$$I_{S_1} = 1.107\times10^{-13}A$$

for Q_1 to be at edge of saturation

$$V_C = V_B = V_X = V_{CC} - I_X R_c \Rightarrow \boxed{R_c = 685.7\,\Omega}$$

1.16



$I_{S1} = 2I_{S2} = 4\times10^{-16}$ A

$\beta_1 = \beta_2 = 100$

$R_1 = 5\,k\Omega$

find V_B such that $I_X = 1$ mA

$$I_X = I_{C1} = I_{S1}\exp\frac{V_{BE1}}{V_T}$$

$$\Rightarrow V_{BE1} = V_T \ln\frac{I_X}{I_{S1}} = 26\times10^{-3}\ln\left(\frac{1\times10^{-3}}{4\times10^{-16}}\right) = 0.792\,V$$

$V_{BE1} = V_B - V_E = V_B \Rightarrow V_B = 0.792\,V$

Other solution :-

$$-V_B + R_1(I_{B1}+I_{B2}) + V_{BE} = 0 \Rightarrow V_B = R_1\left[\frac{I_{C1}}{\beta_1}+\frac{I_{C2}}{\beta_2}\right] + V_{BE}$$

$I_{C1} = I_{S1}\exp\frac{V_{BE1}}{V_T}$ $\quad V_{BE1} = V_{BE2}$

$I_{C2} = I_{S2}\exp\frac{V_{BE2}}{V_T}$ $\quad I_{C1} = 2I_{C2}$

$I_{B1}+I_{B2}$

$\frac{I_{C1}}{\beta}+\frac{I_{C2}}{\beta}$

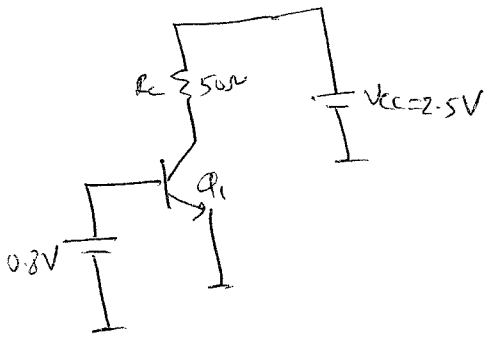
$\frac{I_{C1}+I_{C2}}{\beta} =$

$$V_B = R_1\left[\frac{3I_X}{\beta}\right] + V_T\ln\left(\frac{I_X}{I_{S1}}\right)$$

$$= 5\times10^3\left(\frac{3\times10^{-3}}{100}\right) + 0.026\ln\left(\frac{1\times10^{-3}}{4\times10^{-16}}\right) = 0.892\,V$$

EX 4.21 (a) determine the operating point and small signal model

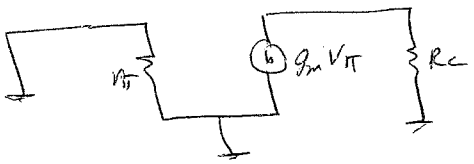
Assume $I_S = 8\times10^{-16}$ A, $\beta = 100$, $V_A = \infty$



If Q is in active mode

$$I_C = I_S\exp\left(\frac{V_{BE}}{V_T}\right) = 8\times10^{-16}\exp\left(\frac{800}{26}\right) = 18.5\,mA$$

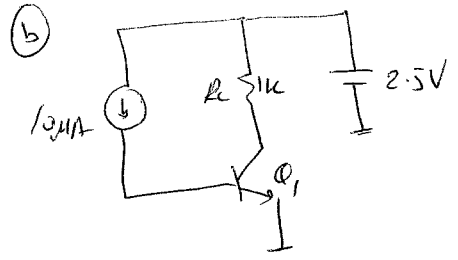
$$V_{CE} = V_{CC} - R_C I_C = 1.575\,V$$



$g_m = \frac{I_C}{V_T}$

$r_\pi = \beta/g_m$

(b)

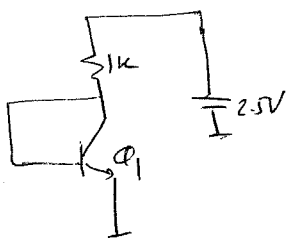


$I_C = \beta I_B = 1$ mA

$V_{CE} = V_{CC} - I_C R_C = 1.5\,V$

$g_m = \frac{I_C}{V_T} = \frac{1}{26}\,\Omega^{-1}$, $r_\pi = \beta/g_m = 2600\,\Omega$

c)



$V_{CC} = R_C I_C + V_{BE}$

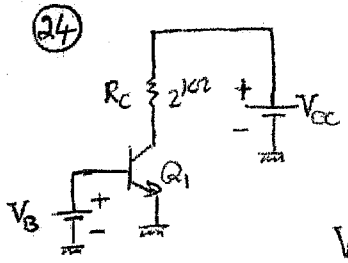
~~2.5 = 1k(I_C) +~~

$V_{CC} = R_C I_S\exp\left(\frac{V_{BE}}{V_T}\right) + V_{BE}$ $\Rightarrow$ $V_{BE} = 739$ mV

$g_m = \frac{I_C}{V_T} = 627$ mS

V_{CC} changes from 2.5V — 3V
$I_S = 1 \times 10^{-17}$ A
$V_A = 5$V
determine the change of collector current

EX27 (24)



$I_S = 1 \times 10^{-17}$ A $V_A = 5^V$

Applying KVL:

$$V_{CC} = R_C I_C + V_{CE}$$

$$\Rightarrow V_{CC} = R_C I_S \exp\left(\frac{V_{BE}}{V_T}\right)\left[1 + \frac{V_{CE}}{V_A}\right] + V_{CE}$$

V_{BE} Constant $\Rightarrow$

$$\boxed{\Delta V_{CC} = \left[R_C I_S \exp\left(\frac{V_{BE}}{V_T}\right)\frac{1}{V_A} + 1\right].\Delta V_{CE}} \quad \text{equation 1}$$

$$I_C = I_S e^{\frac{V_{BE}}{V_T}}\left[1 + \frac{V_{CE}}{V_A}\right] \Rightarrow \Delta I_C = I_S e^{\frac{V_{BE}}{V_T}} \times \frac{1}{V_A}\Delta V_{CE}$$

$$\Rightarrow \boxed{\Delta V_{CE} = \frac{1}{I_S e^{\frac{V_{BE}}{V_T}} \times \frac{1}{V_A}}.\Delta I_C} \quad \text{equation 2}$$

equations 1, 2 $\Rightarrow$

$$\Delta I_C = \frac{I_S e^{\frac{V_{BE}}{V_T}} \times \frac{1}{V_A}}{1 + R_C I_S e^{\frac{V_{BE}}{V_T}} \times \frac{1}{V_A}}.\Delta V_{CC}$$

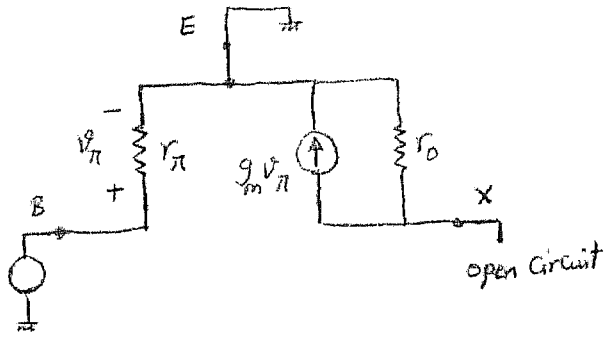
$$\Rightarrow \boxed{\Delta I_C = \frac{I_S \exp\left(\frac{V_{BE}}{V_T}\right)}{V_A + R_C I_S \exp\left(\frac{V_{BE}}{V_T}\right)}.\Delta V_{CC}} = \frac{1}{r_o + R_C}.\Delta V_{CC}$$

Could also be obtained using small signal model

$$\Rightarrow \Delta I_C = \frac{3.31 \times 10^{-4}}{5 + 0.4613} \times 0.5 \Rightarrow \Delta I_C \simeq 0.021\text{mA}$$

(44) Continued .....

c)



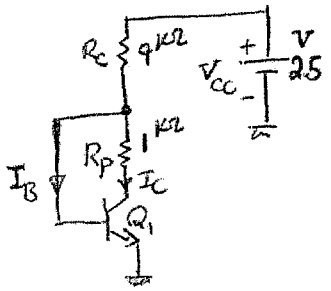
$$r_o = \frac{V_A}{I_C} = \frac{5^V}{2^{mA}} \Rightarrow \boxed{r_o \simeq 2.5\ k\Omega}$$

$$g_m = \frac{I_C}{V_T} = \frac{2^{mA}}{0.026\ V} \Rightarrow \boxed{g_m \simeq 76.9\ mS}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{\frac{2}{26}} \Rightarrow \boxed{r_\pi = 1.3\ k\Omega}$$

36 If V_{BC} = 200mV
find I_S ??

(32) $\beta = 100$, $V_A = \infty \Rightarrow r_o = \infty$



$V_{BC} = 0.2\,V \Rightarrow R_p I_C = 0.2\,V$

$$\Rightarrow \boxed{I_C = \frac{0.2\,V}{R_p}}$$

$$V_{BE} = V_{CC} - R_c(I_B + I_C)$$

$$\overset{\beta=100}{\Rightarrow} V_{BE} = V_{CC} - \frac{\beta+1}{\beta} R_c I_C \Rightarrow \boxed{V_{BE} = V_{CC} - \frac{\beta+1}{\beta}\frac{R_c}{R_p} \times 0.2}$$

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \Rightarrow I_S = I_C \exp\left(-\frac{V_{BE}}{V_T}\right)$$

$$\Rightarrow \boxed{I_S = \frac{0.2}{R_p} \exp\left[\frac{0.2}{V_T}\cdot\frac{\beta+1}{\beta}\cdot\frac{R_c}{R_p} - \frac{V_{CC}}{V_T}\right]}$$

$$\overset{\beta=100}{\Rightarrow} \boxed{I_S \simeq \frac{0.2}{R_p} \exp\left[\frac{0.2}{V_T}\frac{R_c}{R_p} - \frac{V_{CC}}{V_T}\right]}.$$

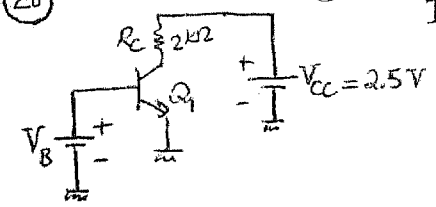
$$\Rightarrow \boxed{I_S \simeq 4.06 \times 10^{-16}\,A}$$

EX32

1) determine V_B such that Q_1 operates at the edge of active region

2) If we allow soft saturation $V_{CB} = 200mV$ by how much can V_B increase?

(28)



$I_S = 6 \times 10^{-16} A$, $V_A = \infty$

a) Q_1 at the edge of the active region $\Rightarrow V_{CE} = V_{BE}$ ($V_C = V_B$, $V_{CE} = V_{BE}$)

applying KVL, $V_{CC} = R_C I_C + V_{CE}$

$\xrightarrow[\text{edge}]{\text{at the}} V_{CC} = R_C I_C + V_{BE} \Rightarrow R_C I_S e^{\frac{V_{BE}}{V_T}} + V_{BE} = V_{CC}$

$\Rightarrow 2^{k\Omega} \times 6 \times 10^{-16} A \; e^{V_B / 26^{mV}} + V_B = 2.5 \Rightarrow \boxed{V_B \simeq 728.5^{mV}}$

b) Applying KVL, $V_{CC} = R_C I_C + V_{CE}$ ($V_C - V_B = 200mA$, $V_{CE} = V_C$, $V_B = V_{BE}$)

Soft saturation $V_{CB} = 200mV$

Soft Saturation $\Rightarrow V_{CE} = V_{BE} - 0.2^V$ $\Rightarrow V_{CE} - V_{BE} = 0.2V$

$\Rightarrow V_{CC} = R_C I_C + V_{BE} - 0.2^V$

$\Rightarrow 2^{k\Omega} \times 6 \times 10^{-16} e^{V_B / 26^{mV}} + V_B = 2.7V$

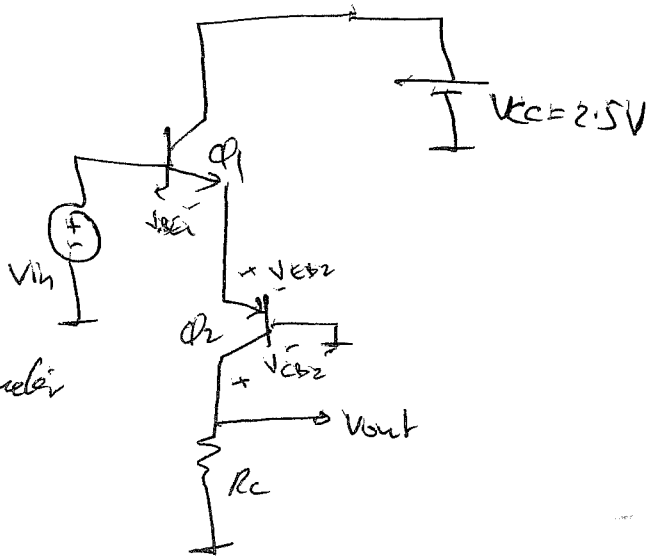
$\Rightarrow \boxed{V_B \simeq 731.5mV}$ So V_B can increase by 3mV

7.53

$I_{S_1} = 3I_{S_2} = 5\times10^{-16}\,A$

$\beta_1 = 100$, $\beta_2 = 50$ $\quad V_A = \infty$, $R_C = 500\,\Omega$

a) We wish to forward bias the collector-base junction of Q_2 by no more than 200mV. What is the max allowable value of V_{in}?



b) Calculate the small signal parameters

$V_{CB_2} < 200\,mV$

$I_{C_2} R_C < 200\,mV$

$\Rightarrow \quad I_{C_2} < 400\,\mu A$

$V_{EB_2} = V_{E_2} = V_T \ln \frac{I_{C_2}}{I_{S_2}} < 741\,mV$

$\frac{\beta_2}{1+\beta_2} I_{E_2} R_C < 200\,mV$

$\frac{\beta_2}{1+\beta_2} \frac{1+\beta_1}{\beta_1} I_{C_1} R_C < 200\,mV \quad \Rightarrow \quad I_{C_1} < 396\,\mu A$

$V_{BE_1} = V_T \ln \frac{I_{C_1}}{I_{S_1}} < 712\,mV$

$\Rightarrow \quad V_{in} = V_{BE_1} + V_{EB_2} < 1.453\,V$

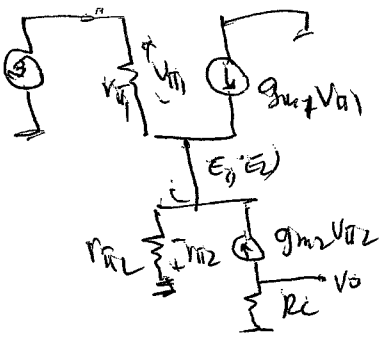
(b) $I_{C_1} = 396\,\mu A$

$I_{C_2} = 400\,\mu A$

$g_{m_1} = \frac{I_{C_1}}{V_T} = 15.2\,mS \qquad g_m = 15.4\,mS$

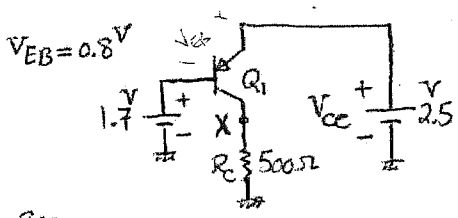
$r_{\pi_1} = \beta / g_{m_1} = 6.56\,k\Omega \qquad r_{\pi_2} = 3.25\,k\Omega$

$r_{O_1} = \infty \qquad r_O = \infty$



44 Calculate V_X

(40) $I_S = 5\times10^{-17}\,A$



a) $V_A=\infty \Rightarrow r_o=\infty$

$$I_C = I_S e^{V_{EB}/V_T} \Rightarrow I_C = 5\times10^{-17} e^{\frac{800}{26}} \Rightarrow \boxed{I_C \simeq 1.15\,mA}$$

$$V_X = R_C I_C = 0.5^{k\Omega} \times 1.15^{mA} \Rightarrow \boxed{V_X \simeq 0.58^V}$$

b) $V_A = 6\,V$

$$I_C = I_S e^{\frac{V_{EB}}{V_T}}\left(1+\frac{V_{EC}}{V_A}\right), \quad V_{EC} = V_{CC} - R_C I_C$$

$$\Rightarrow I_C = I_S e^{V_{EB}/V_T}\left(1+\frac{V_{CC}-R_C I_C}{V_A}\right)$$

$$\Rightarrow I_C = I_S e^{V_{EB}/V_T}\left(1+\frac{V_{CC}}{V_A}\right) - \frac{I_S R_C}{V_A} e^{\frac{V_{EB}}{V_T}} I_C$$

$$\Rightarrow \boxed{I_C = \frac{I_S e^{V_{EB}/V_T}\left(1+\frac{V_{CC}}{V_A}\right)}{1+\frac{I_S R_C}{V_A} e^{V_{EB}/V_T}}} = \frac{5\times10^{-17} e^{\frac{800}{26}}\left(1+\frac{2.5}{6}\right)}{1+\frac{5\times10^{-17}\times0.5^{k\Omega}}{6} e^{\frac{800}{26}}}$$

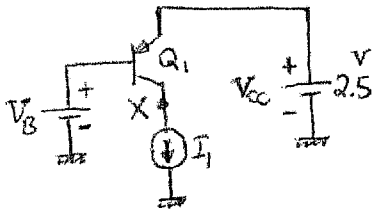
$$\Rightarrow \boxed{I_C = 1.49\,mA} \qquad V_X = R_C I_C = 500\times1.49\times10^{-3} \Rightarrow \boxed{V_X = 0.745^V}$$

Ex 4.9

$I_S = 6\times10^{-16}\,A$
$V_A = 5\,V$
$I_1 = 2\,mA$

a) What V_B for $V_X = 1\,V$?
b) If V_B changes by 0.1 mV find the change of V_X
c) Construct the small signal Model

(44) $I_S = 6\times10^{-16}\,A$, $V_A = 5\,V$, $I_1 = 2\,mA$



a) $I_C = I_S e^{\frac{V_{EB}}{V_T}}\left(1+\frac{V_{EC}}{V_A}\right)$

$$\Rightarrow V_{EB} = V_T \ln\left(\frac{I_C}{I_S\left(1+\frac{V_{EC}}{V_A}\right)}\right)$$

$V_{EC} = V_{CC} - V_X$, $V_{EB} = V_{CC} - V_B$

$$\boxed{V_B = V_{CC} - V_T \ln\left(\frac{I_C}{I_S\left(1+\frac{V_{CC}-V_X}{V_A}\right)}\right)}$$

$$\Rightarrow V_B = 2.5 - 0.026 \ln\left(\frac{2\times10^{-3}}{6\times10^{-16}\left(1+\frac{2.5-1}{5}\right)}\right) \Rightarrow \boxed{V_B \simeq 1.757\,V}$$

b) $I_C = I_S e^{\frac{V_{EB}}{V_T}}\left(1+\frac{V_{EC}}{V_A}\right) \Rightarrow 1+\frac{V_{EC}}{V_A} = \frac{I_C}{I_S} e^{-\frac{V_{EB}}{V_T}}$

$V_{EC} = V_{CC} - V_X$, $V_{EB} = V_{CC} - V_B$

$$\boxed{V_X = V_{CC} - V_A\left(\frac{I_C}{I_S} e^{-\frac{V_{EB}}{V_T}} - 1\right)}$$

$$\Delta V_X \simeq \frac{dV_X}{dV_{EB}}\Delta V_{EB} \Rightarrow \Delta V_X \simeq \frac{V_A}{V_T}\cdot\frac{I_C}{I_S} e^{-\frac{V_{EB}}{V_T}} \Delta V_{EB}$$

$\Delta V_{EB} = -\Delta V_B$

$$\boxed{\Delta V_X \simeq -\frac{V_A}{V_T}\cdot\frac{I_C}{I_S} e^{-\frac{V_{EB}}{V_T}} \Delta V_B}$$

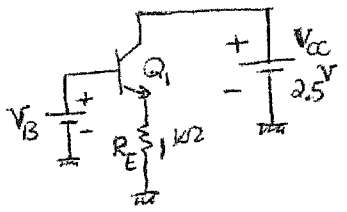
$$\Rightarrow \Delta V_X \simeq -\frac{5}{0.026}\times\frac{2\times10^{-3}}{6\times10^{-16}} \exp\left(-\frac{2.5-1.757}{0.026}\right)\times 0.1\times10^{-3} \Rightarrow \boxed{\Delta V_X \simeq -24.9\,mV}$$

Ex: 4.34

If $V_{BC} = 200mV$

find I_C?

(30) $I_S = 5\times10^{-16}A$, $V_A = \infty \Rightarrow r_o = \infty$



Soft Saturation $\Rightarrow V_{BC} = 200mV$

$V_{BC} = V_B - V_C \Rightarrow \Rightarrow V_B = V_C + 0.2^V \Rightarrow \boxed{V_B = 2.7\,V}$

Applying KVL $\Rightarrow V_B = V_{BE} + R_E I_E \xrightarrow{I_E \simeq I_C} V_B = V_{BE} + R_E I_C$

$\Rightarrow V_{BE} + 1^{k\Omega} \times I_S e^{\frac{V_{BE}}{V_T}} = 2.7^V$

$\Rightarrow V_{BE} + 5\times10^{-13} e^{\frac{V_{BE}}{V_T}} = 2.7^V \Rightarrow \boxed{V_{BE} \simeq 754\,mV}$

$I_C = I_S e^{V_{BE}/V_T} = 5\times10^{-16} e^{\frac{0.754}{0.026}} \Rightarrow \boxed{I_C \simeq 2\,mA}$

4.38

34 In the circuit of Fig. 4.69, calculate the value of I_C, if $\beta = 100$ and $I_S = 6 \times 10^{-16}$ A.

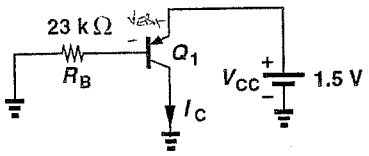


Figure 4.69

Solution

$$V_{CC} = V_{EB} + R_B I_B$$

$$= V_{EB} + R_B \frac{I_C}{\beta}$$

$$1.5 = V_{EB} + 23 \times 10^3 \times \frac{I_S e^{V_{BE}/V_T}}{\beta}$$

$$1.5 = V_{EB} + 23 \times 10^3 \times \frac{6 \times 10^{-16} \times e^{V_{BE}/0.026}}{100}$$

$$V_{EB} = 0.762 \text{ V}$$

$$I_C = 3.20 \text{ mA}.$$

2587

38 Calculate the collector currnt of *Q1* in Fig 4.73, if I_S=3× 10^{-17} A.

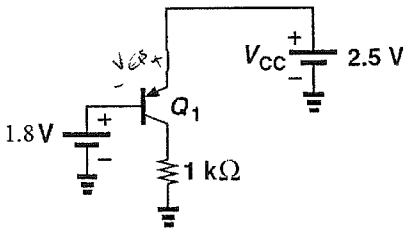


Figure 4.73

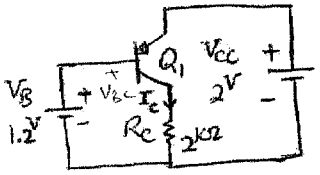
Solution

$$V_{EB} = 2.5V - 1.8V$$
$$= 0.7\,\text{V}$$
$$I_C = I_S e^{V_{BE}/V_T}$$
$$= 3\times10^{-17} \times e^{0.7/0.026}$$
$$= 1.477\times10^{-5}\ \text{A}.$$

EX: 4.40 Find I_S such that Q operates at the edge active mode

(36) At the edge of active $\Rightarrow V_{BC} = 0$

$V_B = V_C \Rightarrow V_{BC} = 0$



$$I_C = \frac{V_B - V_{BC}}{R_C} = \frac{V_B}{R_C}$$

$$\Rightarrow I_C = \frac{1.2^V}{2K\Omega} \Rightarrow \boxed{I_C \simeq 0.6\ mA}$$

$$I_C = I_S \exp\left(\frac{V_{EB}}{V_T}\right) \Rightarrow I_S = I_C \exp\left(-\frac{V_{EB}}{V_T}\right)$$

$$\Rightarrow I_S = 0.6 \times 10^{-3} \exp\left(-\frac{800}{26}\right)$$

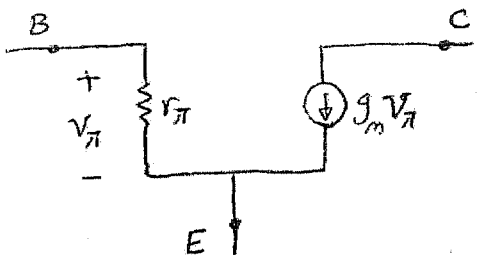
$$\Rightarrow \boxed{I_S \simeq 2.6 \times 10^{-17}\ A}$$

Ex:23 BJT has $I_C = I_S \exp \frac{V_{BE}}{nV_T}$
Construct the small signal model
if I_C is still equal βI_B

(20) $I_C = I_S \exp\left(\frac{V_{BE}}{nV_T}\right)$ $\qquad I_C = \beta I_B$

$$g_m = \frac{\partial I_C}{\partial V_{BE}} = \frac{1}{nV_T} I_S \exp\left(\frac{V_{BE}}{nV_T}\right) = \frac{I_C}{nV_T}$$

$$r_\pi = \frac{\partial V_{BE}}{\partial I_B} = \frac{\partial V_{BE}}{\frac{1}{\beta}\partial I_C} = \frac{\beta}{g_m} = \frac{n\beta V_T}{I_C}$$

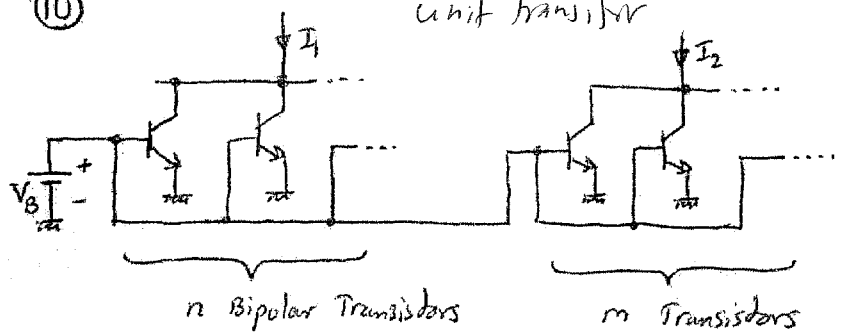


Ex: 4.12 $I_1 = 1mA$, $I_2 = 1.5mA$

$I_S = 3 \times 10^{-16} A$

Construct the required circuit with minimum number of unit transistor

(10)



$$I_1 = n I_C = n I_S e^{V_B/V_T}$$

$$I_2 = m I_C = m I_S e^{V_B/V_T}$$

$$\Rightarrow \frac{I_1}{I_2} = \frac{n}{m}$$

$$\Rightarrow \boxed{\frac{n}{m} = \frac{1mA}{1.5mA} = \frac{2}{3}} \xrightarrow{\text{Choose}} \boxed{\begin{matrix} n=2 \\ m=3 \end{matrix}}$$

$$I_1 = n I_C = n I_S e^{\frac{V_B}{V_T}}$$

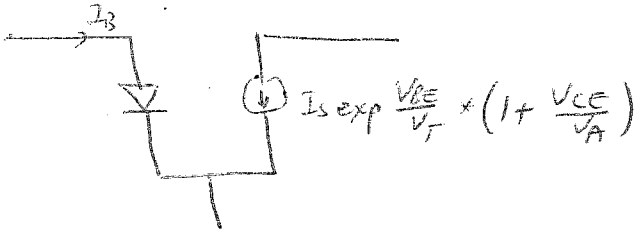
$$\Rightarrow I_1 = n \times 3 \times 10^{-16} e^{\frac{V_B}{26m}} = 1^{mA} \quad \xrightarrow{n=2} \quad \boxed{V_B \simeq 750^{mV}}$$

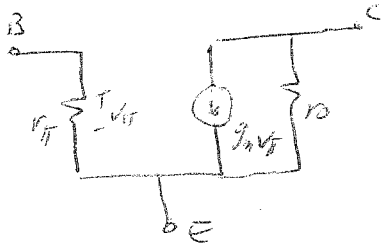
Chapter 5
lect. 20

Today's lect.
- Introduction to Amplifiers
- Common Emitter topology.

- Amplifiers:

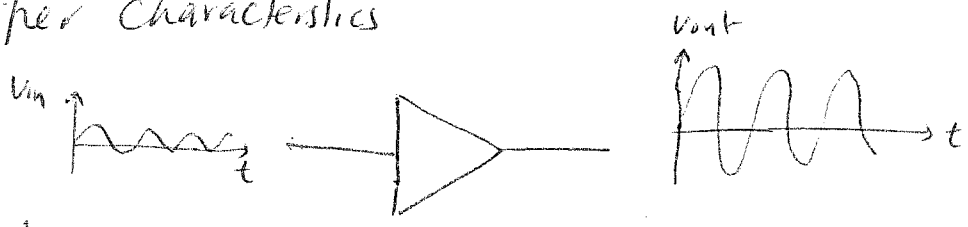
Bipolar Transistor Models





* Design Procedure:-
a) Select a topology
(b) Create proper bias conditions for all transistors.
(c) Analyze the small signal properties of the amplifier and see if they are satisfactory.

* Amplifier Characteristics

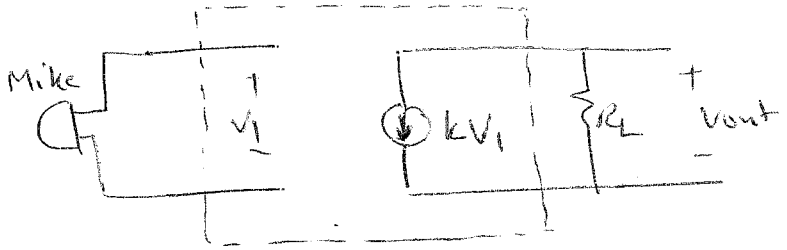


1) * Voltage gain = $\frac{\text{Output Swing}}{\text{input swing}}$

$$A_v = \frac{V_{out}}{V_{in}}$$

2) Power Consumption: bias current drain the battery.

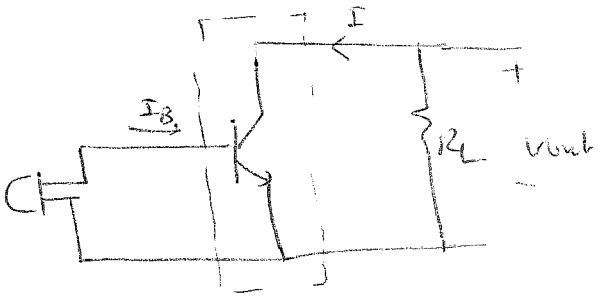
Let's build an amplifier:



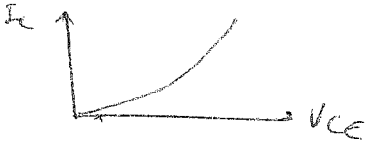
$V_{out} = -kR_L V_{in}$

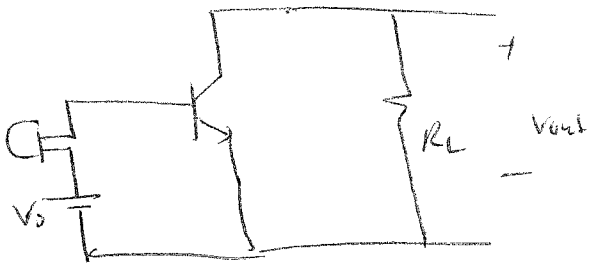
$A_v = \frac{V_{out}}{V_{in}} = -kR_L$

- $\overrightarrow{V/I}$ conversion
- The resistor convent $\overrightarrow{I/V}$

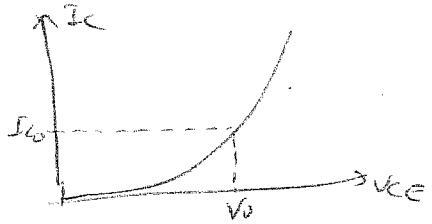


This is not work because there is not ~~bias~~ bias





- V_0 is generate bias current

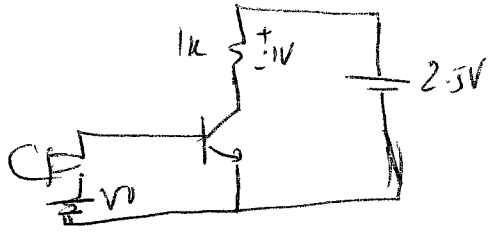


We still have problem, because BJT must work in the active forward mode. (because V_{CB} must be reverse biasy because, we can't have no current of I_C

$V_{out} = -R_L I_{C0} \rightarrow$

example if $I_{C0} = 1mA$
$R_L = 1k$ $\Rightarrow$ $V_{out} = -1V = V_C$

for input side: So we need V_C to be more voltage than V_B
So it can done by adding a battery



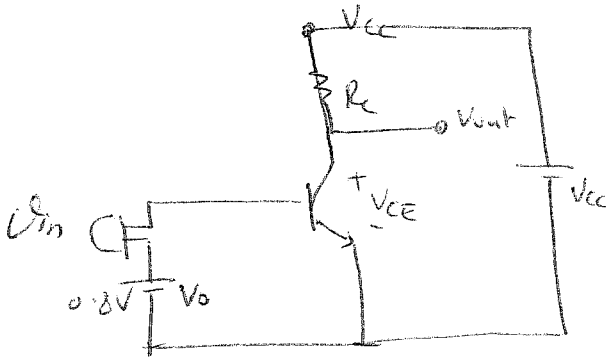
If $V_0 = 0.8V$
$\Rightarrow V_{BE} = 0.8V$
$I_{C0} = 1mA$

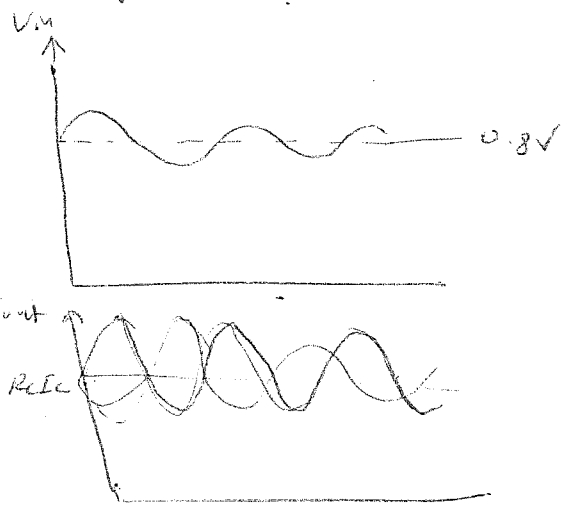
$V_{CE} = 1.5V$
$V_C = 1.5V$
$V_B = 0.8V$
$V_C > V_B$ in reverse

So after select the proper biasing the transistor becomes amplifier.

Common Emitter Amplifier

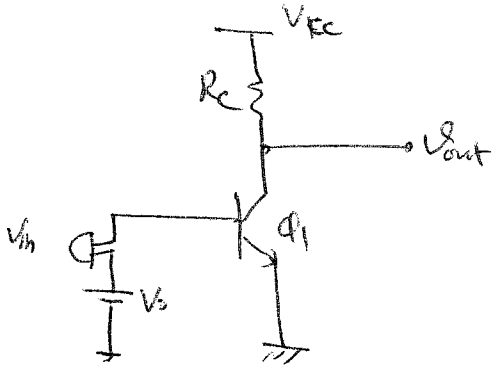
Emitter is common for both input and output port



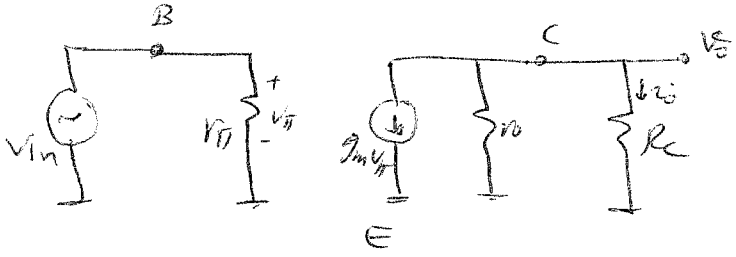


$$V_{out}\Big|_{dc} = V_{cc} - R_c I_c = V_{CE}$$

* Simplified Diagram



- Small Signal Voltage gain Calculation



1) Assume $A_V = \infty \Rightarrow r_o = \infty$)

$$v_o = i_o R_c$$
$$= -g_m v_\pi R_c$$
$$= -g_m v_{in} R_c$$

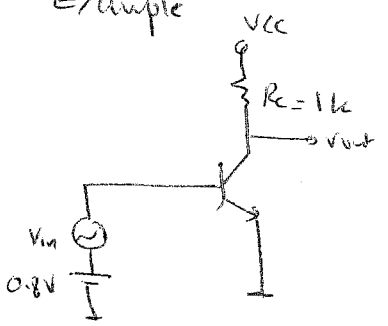
$$\boxed{A_v \quad \frac{v_o}{v_{in}} = -g_m R_c}$$

↓ means phase shift of 180°

For the CE:

$A_v = -g_m * (\text{total resistance tied between the collector and the ac ground})$

Example



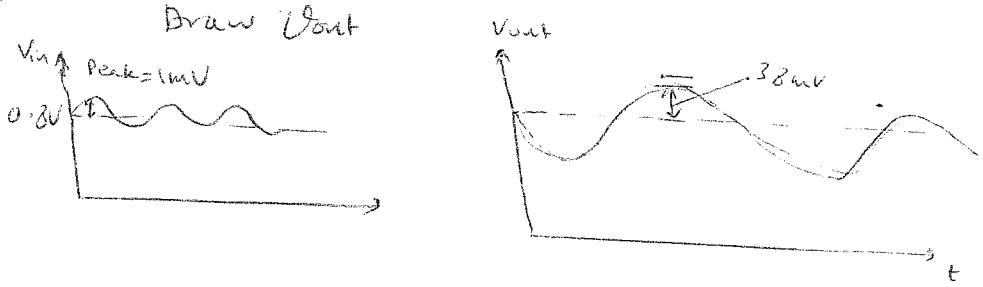
Find A_v

Assume $I_c = 1mA$

$\Rightarrow g_m = \frac{I_c}{V_T} = \frac{1}{26\Omega}$

$\Rightarrow A_v = -g_m R_c = -\frac{1000}{26} = -38$

Draw Vout



* If we need to double the gain

$A_v = -g_m R_c \longrightarrow$ To double the gain, $R_c \longrightarrow 2R_c$

* To see if everything is ok, we have to test the biasing condition

$$V_{out}\Big|_{dc} = V_{cc} - 2R_c I_c$$
$$= 2.5 - 2 \times 1k \times 1mA = 0.5V$$

It's become problem because $V_C < V_B \Rightarrow$ Saturation condition

but the transistor is in the active region

$\Rightarrow$ **The voltage headroom is limited as R_c increases**

* To double the gain

Let's double g_m instead

$$A_v = -g_m R_c = -\frac{I_c}{V_T} R_c$$

Double g_m can done by double I_c

$$V_{out}|_{dc} = V_{cc} - R_c I_c$$

double

$$= V_{cc} - 2R_c I_c$$
$$= 2.5 - 2 \times 1K \times 1mA = 0.5\ mA$$

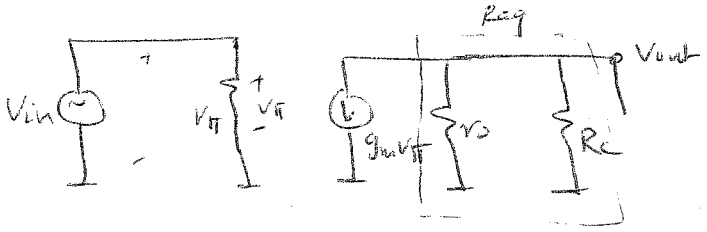
$\Rightarrow$ $I_c R_c$ doubles $\rightarrow$ $\boxed{V_{CE} = 0.5mA}$, we have the same problem $\Rightarrow$ Q goes in saturation.

---

* Inclusion of Early Effect:

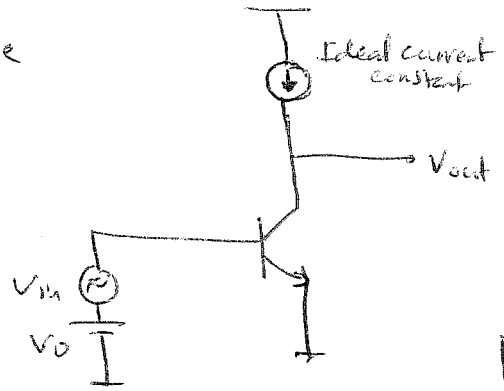
$A_v = -g_m \times$ (Total Resistance at collector and ground)

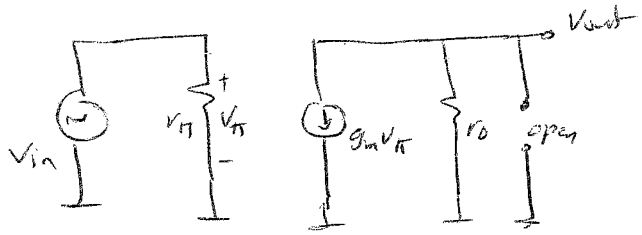
$A_v = -g_m (R_c // r_o)$



(*) the early Effect $\rightarrow$ reduces the gain.

Example





$$\boxed{A_v = -g_m r_o}$$

$$= -\frac{I_c}{V_T}\frac{V_A}{I_c} = -\frac{V_A}{V_T}$$

this is $(g_m r_o)$ is intrinsic gain of the transistor because is the highest gain can be obtain. not dependent on the biasing conditions.

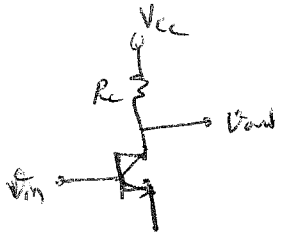
lect. 21

Today's lect.

* Problem of Input Impedance
* Problem of Output Impedance

Review:

* CE gain



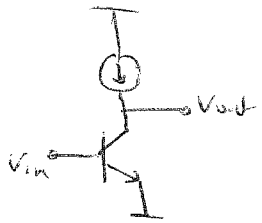
$$\frac{v_o}{v_{in}} = -g_m R_c$$

$$= \frac{-I_c R_c}{V_T}$$

$$V_{CE} = V_{cc} - R_c I_c$$

* Inclusion of Early Effect

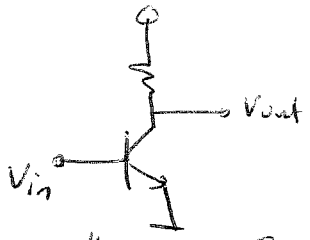
$$A_v = -g_m (R_c \| r_o)$$



$R_c \to \infty$, $A_v = -g_m r_o$

that means when R_c is replace by ideal Current source.

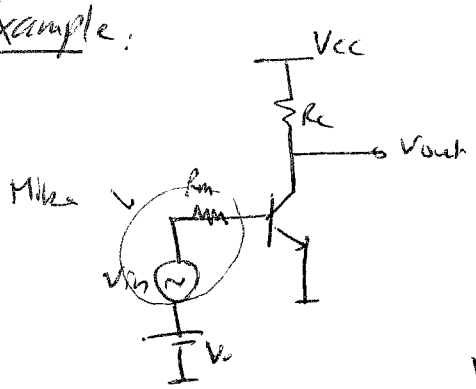
* How we de identify a Common ~~Source~~ Emitter stage,
  - Input is applied to base
  - Output is taken from Collector



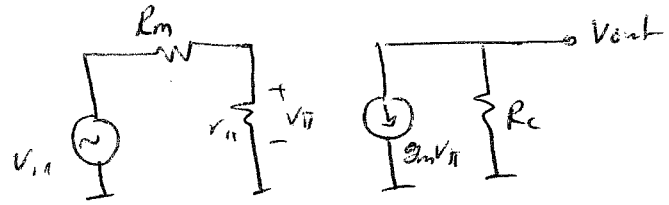
? Can we apply the input to the emitter or Collector?

* Can we taken the output at the emitter or base?

Example:



* Replace the Mike by (v_{in} and internal resistance R_m)



$$V_\pi = \frac{r_\pi}{r_\pi + R_m} v_{in}$$

$$v_{out} = -g_m v_\pi R_c$$

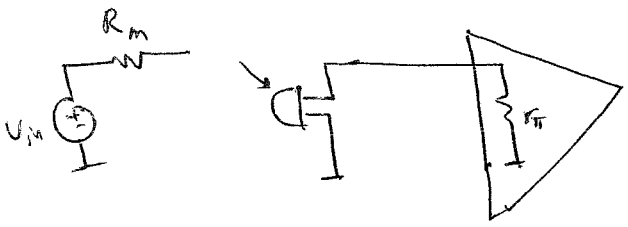
$$= -g_m R_c \left[\frac{r_\pi}{r_\pi + R_m}\right] v_{in}$$

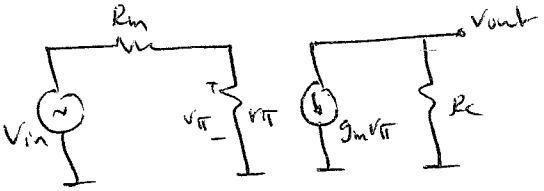
$$\boxed{A_v = -g_m R_c \left(\frac{r_\pi}{r_\pi + R_m}\right)} \leftarrow \text{attenuation factor.}$$

If $R_m = r_\pi$ = $A_v = -\frac{1}{2} g_m R_c$

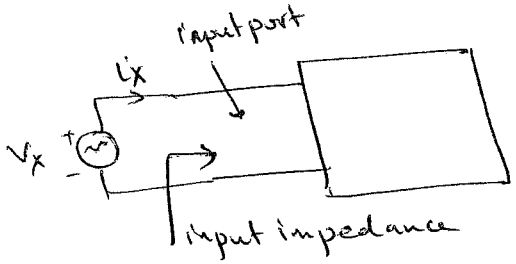
that means the gain becomes the half.

that means, we see that R_m makes the attenuation by the factor of $\left(\frac{r_\pi}{r_\pi + R_m}\right)$.

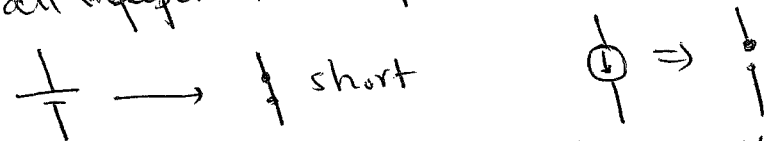




* <u>The input impedance :</u>

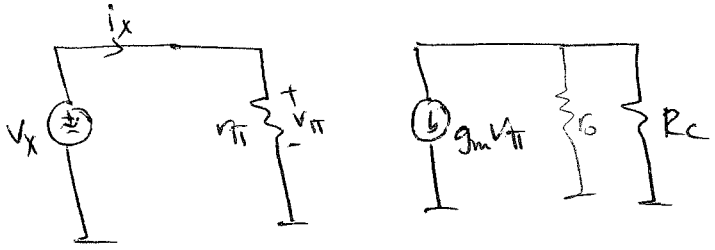


① Set all ~~independt~~ independent source to zero.



② Apply a small signal voltage source between the input terminals (V_x). Calculate the current supplied by this voltage source

$$\Rightarrow R_{in} = \frac{v_x}{i_x}$$



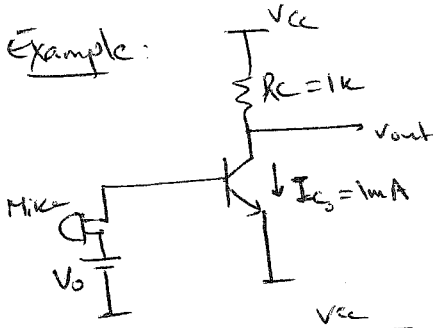
- To Calculate the input impedance / we don't include the resistance of the mike.

$$V_x = r_\pi i_x \quad \Rightarrow \quad R_{in} = \frac{V_x}{i_x} = r_\pi$$

- If we has r_o $\Rightarrow$ doesn't effect the value of r_π.

Output Impedance:-

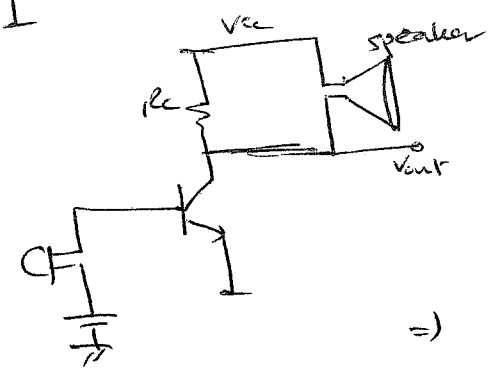
Example:



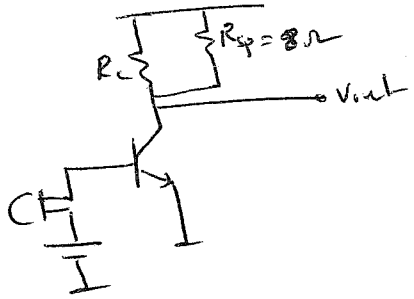
- $V_A = \infty$
- $A_v = -g_m R_c = -38$.

If we drive a speaker as shown

Replace the speaker by a resistor



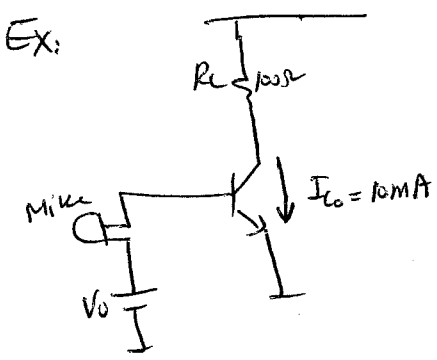
$\Rightarrow$



$$\Rightarrow A_v = -g_m (R_c \| R_{sp})$$
$$= -g_m (1k \| 8\Omega) = -0.3$$

When we connect the speaker, the gain drops the gain to be less than 1.

Ex:

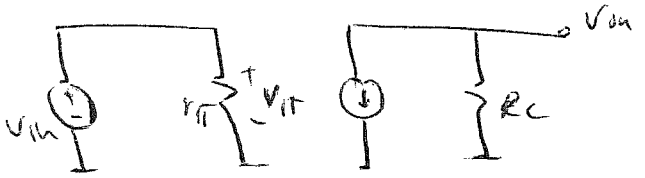


$$A_v = -g_m R_c = -\frac{I_C R_c}{V_T}$$
$$= -38$$

after connect the speaker.

$$A_v = -g_m (R_c \| R_{sp})$$
$$= -g_m (100 \| 8) = -7.3$$
$$\simeq -(2.8)$$

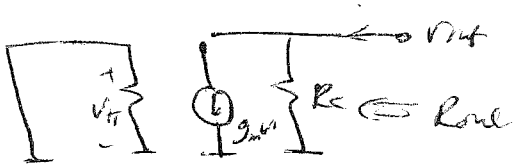
Using Small Signal Model



$$v_o = -g_m R_C v_{in}$$

To Calculate Rout

$$R_{out} = \frac{v_{out}}{i_{out}}\Big|_{v_{in}=0}$$

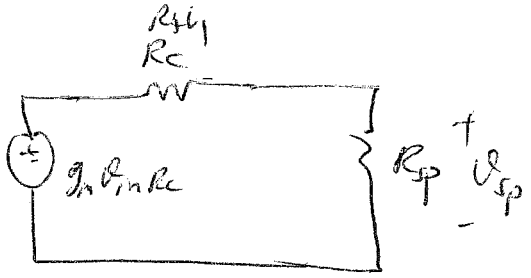


when $v_{in} = 0 \Rightarrow v_\pi = 0$

$g_m v_\pi = 0 \Rightarrow$ open circuit

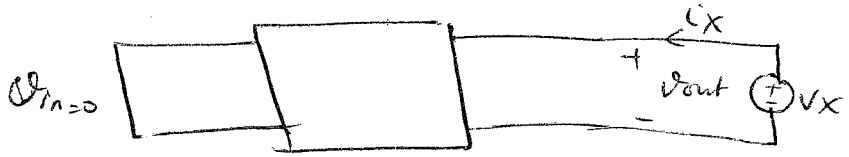
$\Rightarrow \boxed{R_{out} = R_C}$

when we connect the speaker



$$v_{sp} = \frac{R_{sp}}{R_{sp} + R_C}(-g_m R_C v_{in})$$

Rout Calculation



$$R_{out} = \frac{v_{out}}{i_X}\Big|_{v_{in}=0}$$

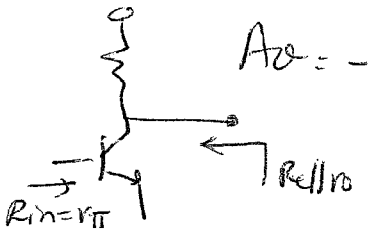
for the Basic CE stage

$$R_{out} = R_C$$

If we include the early effect

$$R_{out} = R_C // r_o$$

Summery



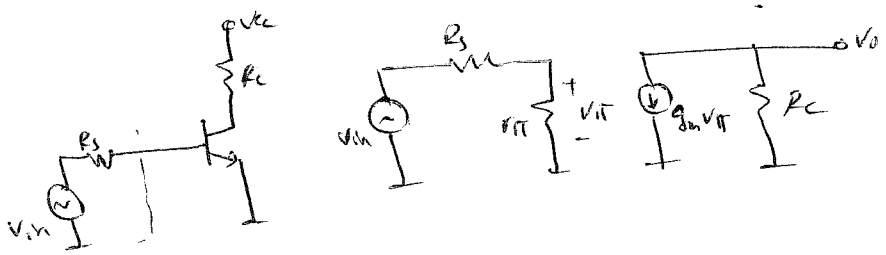
$$A_v = -g_m(R_C // r_o)$$

Today's lect.

- Cascaded stages
- Problem of gain variation
- CE stage with Emitter degeneration

Review of lect 21

- Problem of Input Impedance

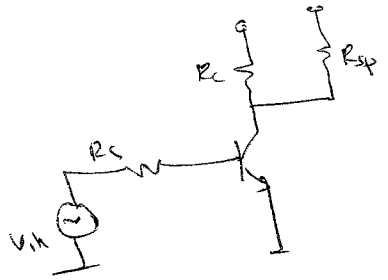


$$A_{\vartheta} = -g_m R_c \left(\frac{r_\pi}{r_\pi + R_m}\right)$$

R_m makes attenuation by the factor

To reduce the attenuation r_π have to be maximum

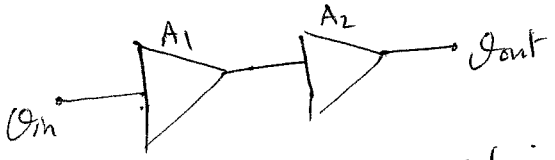
- Problem of output impedance

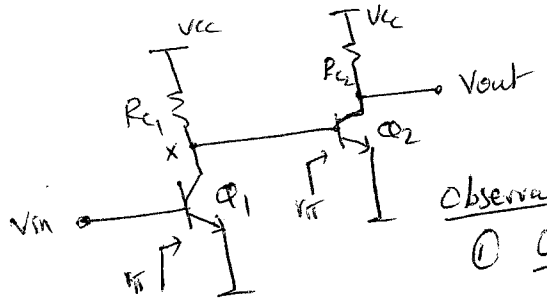


$$A_{\vartheta} = -g_m (R_c // R_{sp}) = -g_m \frac{R_c R_{sp}}{R_c + R_{sp}}$$

↓ ⇒ reduces the gain

Cascaded Stages:-

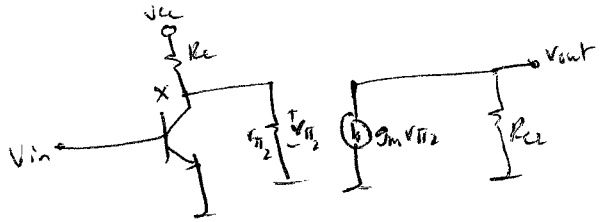




Two stage amplifier.
Cascaded amplifier

Observation

$$① \quad \frac{\vartheta_{out}}{\vartheta_{in}} = \underbrace{\frac{\vartheta_x}{\vartheta_{in}}}_{A\vartheta_1} * \underbrace{\frac{\vartheta_{out}}{\vartheta_x}}_{A\vartheta_2} = A\vartheta_1 \times A\vartheta_2$$



$V_A = \infty$

② $A_{v_1} = -g_{m_1}(R_{C_1} \| r_{\pi_2})$

$A_{v_2} = \frac{v_{out}}{v_x} = -g_{m_2} R_{C_2}$

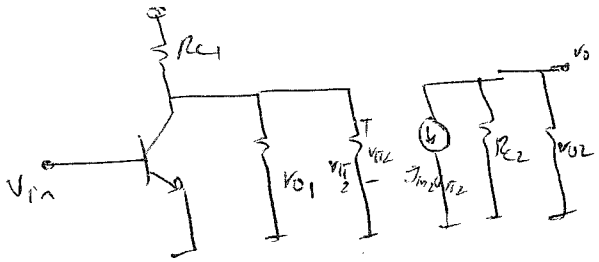
③ $A_v = \frac{v_{out}}{v_{in}} = g_{m_1} g_{m_2} (R_{C_1} \| r_{\pi_2}) * R_{C_2}$

Quiz: Find the gain if $V_A \neq \infty$

$A_{v_1} = -g_{m_1}(R_{C_1} \| r_{O_1} \| r_{\pi_2})$

$A_{v_2} = -g_{m_2}(R_{C_2} \| r_{O_2})$

$A_v = g_{m_1} g_{m_2} (R_{C_1} \| r_{O_1} \| r_{\pi_2})(R_{C_2} \| r_{O_2})$



* Problem of gain Variation

If $V_A = \infty$ $\quad A_v = -g_m R_C = -\frac{I_C R_C}{V_T}$

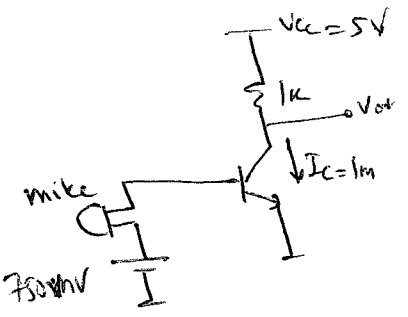
① Variation with Temperature and Process

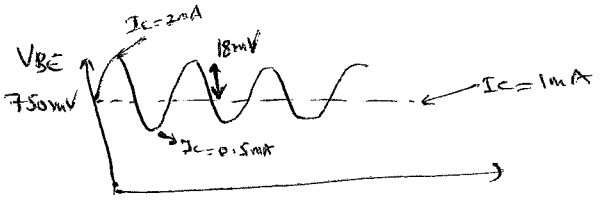
ⓧ $I_C = I_S \exp \frac{V_{BE}}{V_T}$ $\quad I_C = f(T)$

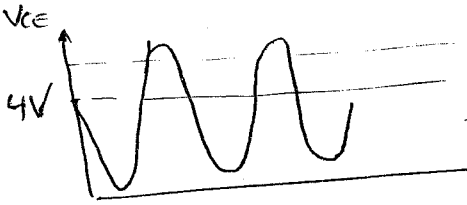
ⓧ Process: because may be Resistance have tolerence maincfacture

② Variation with Signal amplitude

the gain is dependent on the amplitude of the input signal







Disteration
non-lineanty

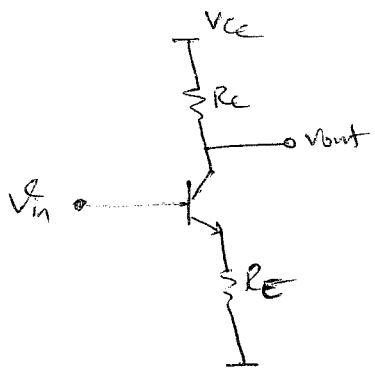
$I_C = I_S \exp \frac{V_{BE}}{V_T}$

$= I_S \exp\left(\frac{750mV + 18}{26}\right)$

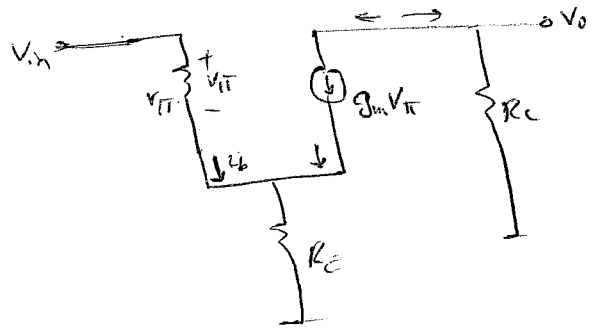
$= I_S \exp \frac{750}{26} * \exp \frac{18}{26} = 1mA * 2 = 2mA$

CE stage with Emitter Degeneration

: Calculation Av



$V_A = \infty$



$$v_{out} = i_o R_c$$

KCL @ output node $\quad g_m V_\pi + i_o = 0$

$$g_m V_\pi + \frac{v_{out}}{R_c} = 0 \Rightarrow V_\pi = -\frac{v_{out}}{g_m R_c}$$

KCL @ the emitter node

$$\frac{V_\pi}{r_\pi} + g_m V_\pi = i_E$$

$$-\frac{v_{out}}{r_\pi g_m R_c} + g_m\left(\frac{-v_{out}}{g_m R_c}\right) = i_E$$

$$V_E = i_E R_E = -v_{out}\left[\frac{1}{r_\pi R_c g_m} + \frac{1}{R_c}\right] R_E$$

KVL @ input node

$$v_{in} = v_\pi + V_E$$

$$= -\frac{v_{out}}{g_m R_c} - v_{out}\left[\frac{1}{r_\pi R_E g_m} + \frac{1}{R_c}\right] R_E$$

$$=$$

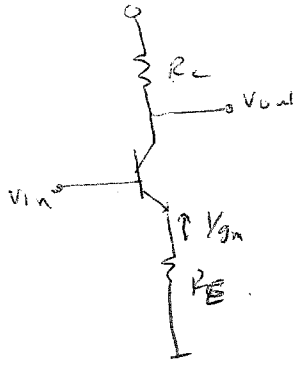
$r_\pi = \beta/g_m \Rightarrow r_\pi g_m = \beta$

$$v_{in} = -\frac{v_{out}}{g_m R_c} - v_{out} R_E\left[\frac{1}{\beta R_c} + \frac{1}{R_c}\right]$$

$$\Rightarrow \frac{v_{out}}{v_{in}} = -\frac{\beta g_m R_c}{\beta + (\beta+1) g_m R_E} \cong -\frac{R_c}{R_E + 1/g_m} \cong -\frac{R_c}{R_E}$$

Assume $\beta \gg 1$ when $R_E = 0 \Rightarrow A_v = -R_c g_m$

For the CE stage with emitter degeneration :-

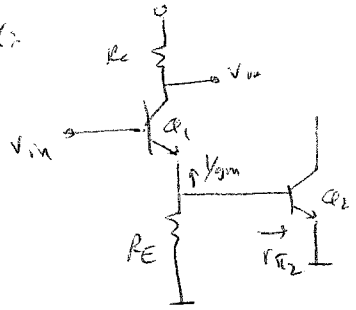


$$A_V = -\frac{R_C}{\frac{1}{g_m} + R_E}$$

$$= -\frac{\text{total resistance connected to Collector}}{1/g_m + \text{total resistance connected to emitter}}$$

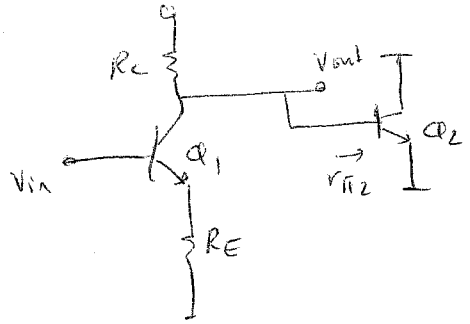
Ex:

a)



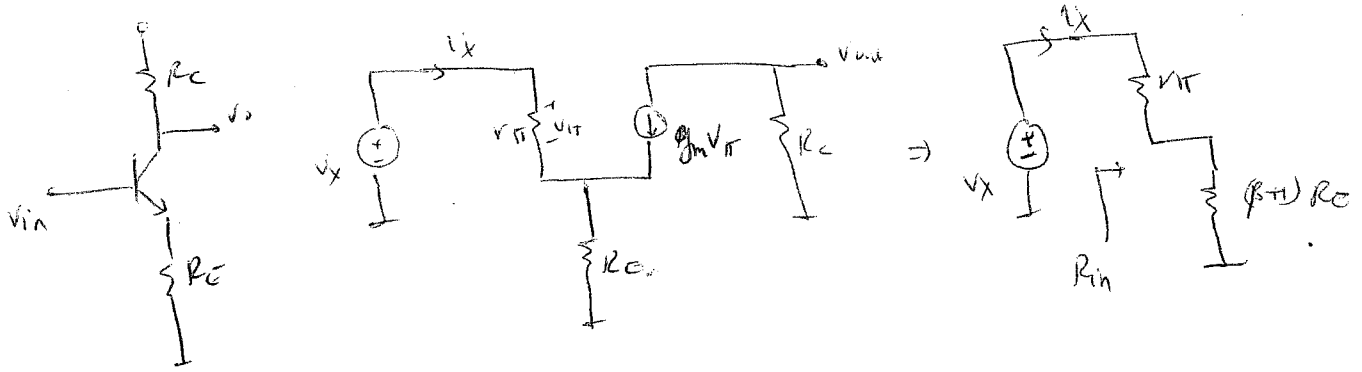
$$A_V = -\frac{R_C}{\frac{1}{g_{m_1}} + R_E /\!/ r_{\pi_2}}$$

b)



$$A_V = \frac{-R_C /\!/ r_{\pi_2}}{1/g_{m_1} + R_E}$$

* Calculate Rin and Rout



$$V_X = V_\pi + i_E R_E$$

$$= r_\pi i_X + R_E (i_X + g_m V_\pi)$$

$$= r_\pi i_X + R_E i_X + R_E g_m r_\pi i_X$$

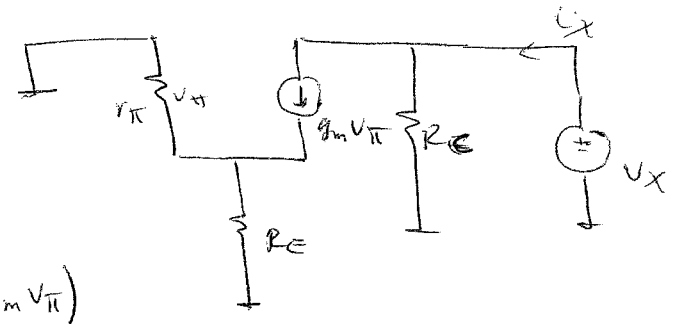
$$= i_X \left[r_\pi + R_E (1 + g_m r_\pi) \right]$$

$$R_{in} = \frac{V_X}{i_X} = r_\pi + R_E (1 + g_m r_\pi)$$

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

Calculate Rout

$$R_{out} = \frac{V_x}{i_x}\Big|_{v_i=0}$$



$$V_{in} = 0$$

$$= v_\pi + R_E\left(\frac{v_\pi}{r_\pi} + g_m v_\pi\right)$$

$$0 = v_\pi\left[1 + R_E\left(\frac{1}{r_\pi} + g_m\right)\right]$$

$$\Rightarrow \quad v_\pi = 0 \quad \Rightarrow \quad g_m v_\pi = 0 \quad \Rightarrow \text{ open circuit}$$

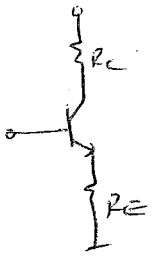
$$\Rightarrow \quad V_x = R_E i_x \quad \Rightarrow \quad \frac{V_x}{i_x} = R_E$$

lect. 23

Today's lect.

- Properties of CE stage with Degeneration
- Input and Output impedances
- Degenerated current source

Review: CE stage with Emitter Degeneration:



$*V_A = \infty$

$$A_v = -\frac{R_C}{\frac{1}{g_m} + R_E}$$

less sensitivities of variation of gain

(*) Properties:

(1) Gain is less sensitive to temp. and process variation and to signal amplitude.

$$A_v = \frac{-R_C}{\frac{1}{g_m} + R_E} = \frac{-R_C}{\frac{V_T}{I_C} + R_E}$$

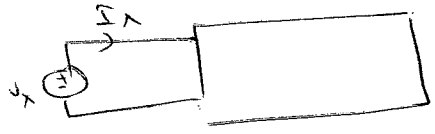
To minimize sensitivity to I_C, pick $R_E \gg \frac{V_T}{I_C}$

$$\boxed{R_E \cdot I_C \gg V_T} \Rightarrow A_v \approx -\frac{R_C}{R_E}$$

(2) The gain is lower with degeneration than without.

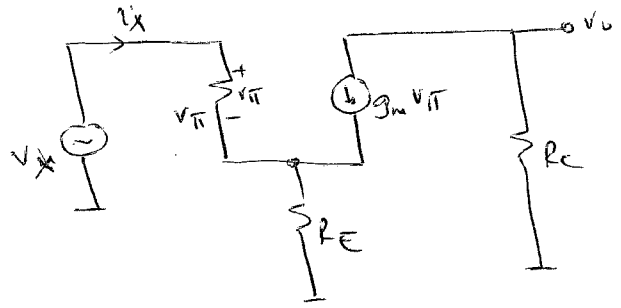
(3) $A_v = -\dfrac{\text{Resistance tied between collector and GND}}{\frac{1}{g_m} + \text{Resistance tied between E and GND}}$

* Input Impedance:



$$R_{in} = \frac{V_X}{I_X}$$

$V_A = \infty$



$$V_\pi = r_\pi i_x$$

KCL @ node of Emitter:-

$$i_e = g_m V_\pi + i_x$$

$$= g_m r_\pi i_x + i_x$$

$$i_e = \beta i_x + i_x$$

$$i_e = (\beta+1) i_x$$

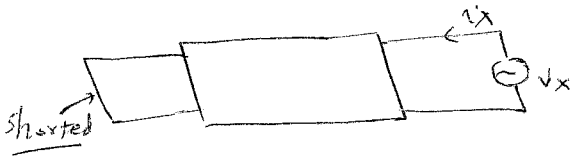
KVL :-

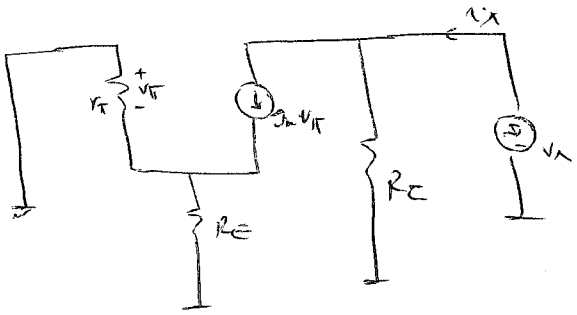
$$V_x = V_\pi + V_{R_E}$$

$$= i_x r_\pi + R_E(\beta+1) i_x$$

$$\boxed{R_{in} = \frac{V_x}{i_x} = r_\pi + R_E(\beta+1)}$$

⊗ Output Impedance : $V_A = \infty$





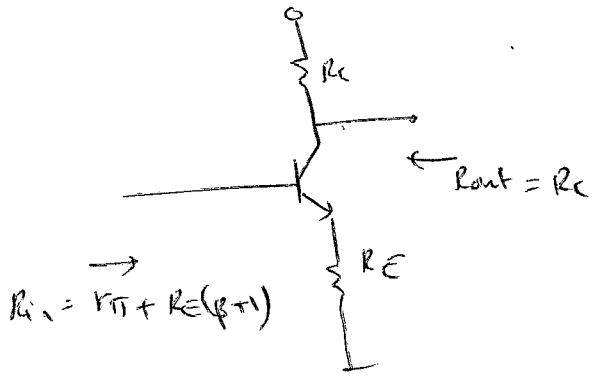
without R_C : $(r_\pi // R_E) \Rightarrow V_\pi = V_{R_E}$

KCL : $\frac{V_\pi}{r_\pi} + g_m V_\pi = -\frac{V_\pi}{R_E}$

$$V_\pi\left(\frac{1}{r_\pi} + g_m + \frac{1}{R_E}\right) = 0 \Rightarrow V_\pi = 0.$$

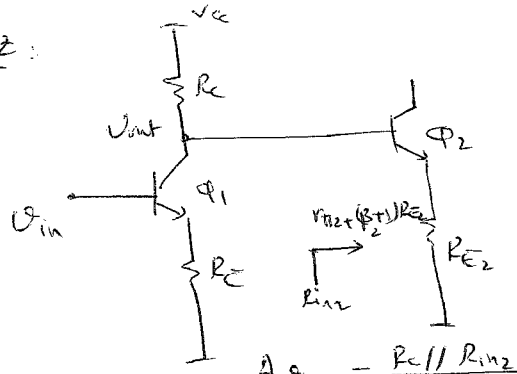
$$\Rightarrow \boxed{\frac{V_x}{i_x} = R_C}$$

Summery :



$$A_v = -\frac{R_C}{\frac{1}{g_m} + R_E}$$

Quiz:



$$A_v = -\frac{R_C \,//\, R_{in2}}{1/g_m + R_E}$$

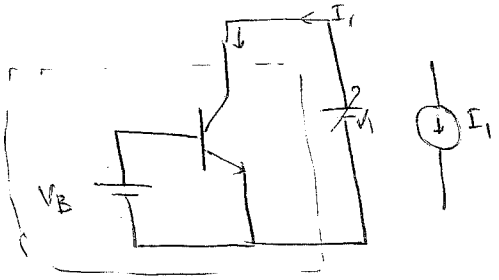
Calculate the voltage gain.

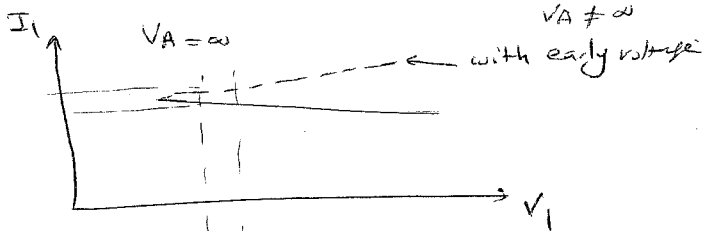
for CE with degeneration

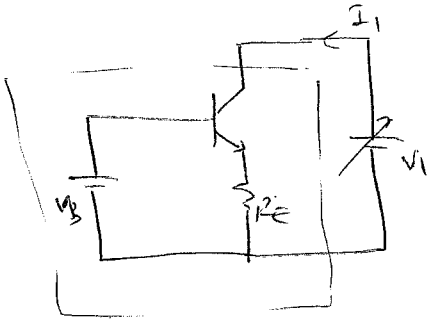
$$A_v = -\frac{\text{Resistance tied between C and GND}}{1/g_m + \text{Resistance tied between E and GND}}$$

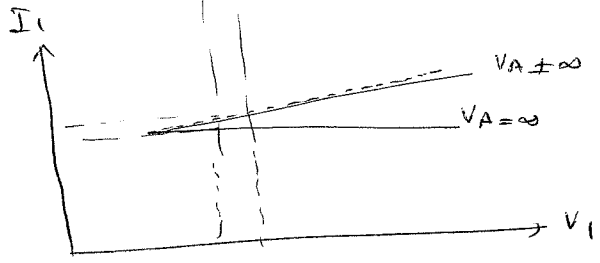
$$\star\quad A_v = -\frac{R_C \,//\, (r_{\pi 2} + (\beta_2+1)R_{E_2})}{1/g_{m_1} + R_{E_1}}$$

* Let's build constant current source:

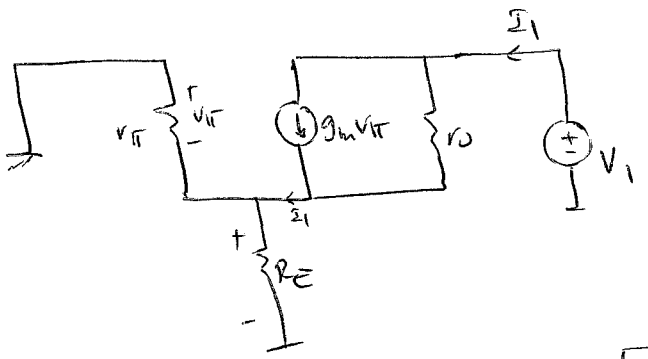








For the second case, we see that the variation of current is less than the first case when $V_A \neq \infty$ => that means we have to consider r_o.



$r_\pi \,//\, R_E$

$V_\pi \neq V_{R_E} = 0$

$$\boxed{V_{R_E} = -V_\pi}$$

KCL @ the emitter node

$$\frac{V_\pi}{r_\pi} + I_1 = -\frac{V_\pi}{R_E}$$

$$-V_\pi\left(\frac{1}{r_\pi} + \frac{1}{R_E}\right) = I_1$$

$$\boxed{-V_\pi = I_1 * (r_\pi \,//\, R_E)}$$

$$I_1 = I_{r_o} + g_m V_\pi$$

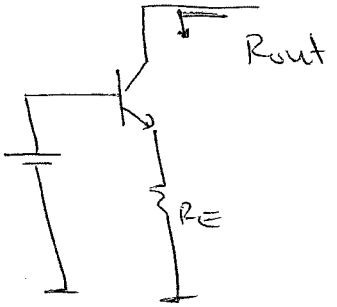
$$I_{r_o} = I_1 - g_m V_\pi = I_1 + g_m I_1 (r_\pi \,//\, R_E)$$

KVL: $V_1 = V_{r_o} + V_{R_E}$

$= r_o\left(i_1 + g_m(r_\pi \| R_E)\, i_1\right) + i_1 (r_\pi \| R_E)$

$\therefore \frac{V_1}{I_1} = r_o\left[1 + g_m(r_\pi \| R_E)\right] + r_\pi \| R_E = R_{out}$

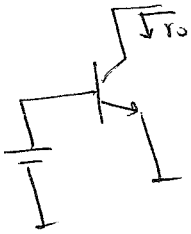
we see that r_o becomes higher that means the current becomes more flat.



$$R_{out} = (1 + g_m r_o)(r_\pi \| R_E) + r_o$$

when $R_E = 0$

$$R_{out} = r_o$$



$V_1 = V_{r_o} + V_{R_E}$

$= r_o\left[I_1 - g_m V_\pi\right] + I_1 (R_E \| r_o)$

KCL @ emitter:

$I_E = \frac{V_E}{R_E} = I_1 + \frac{V_\pi}{r_\pi}$

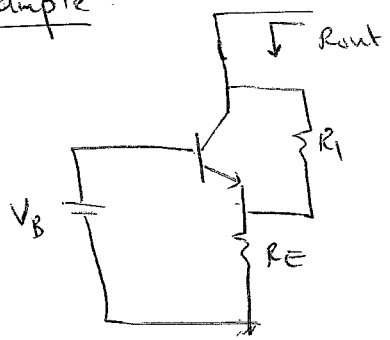
KVL: $V_\pi + V_E = 0 \Rightarrow V_E = -V_\pi$

$-\frac{V_\pi}{R_E} = I_1 + \frac{V_\pi}{r_\pi}$

$-V_\pi\left[\frac{1}{r_\pi} + \frac{1}{R_E}\right] = I_1$

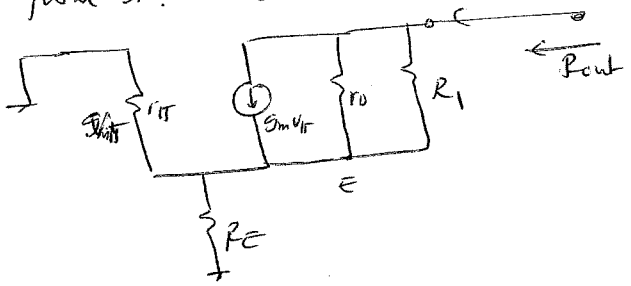
$-V_\pi \frac{r_\pi R_E}{r_\pi + R_E} = I_1 (r_\pi \| R_E)$

Example



Calculate Rout.

from small signal we know that

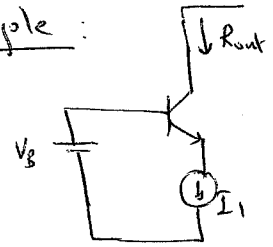


The same answer before but $(r_o \| R_1)$

$$\Rightarrow \quad R_{out} = \left[1 + g_m(r_o \| R_1)\right]\left[(r_\pi \| R_E)\right] + (r_o \| R_1)$$

the same result but replacing R_E by ∞

Example:



$R_{out} = (1 + g_m r_o)(r_\pi \| \infty) + r_o$

$= (1 + g_m r_o)\, r_\pi + r_o$

$= r_\pi + \underbrace{g_m r_\pi}_{\beta} r_o + r_o = (\beta + 1) r_o + r_\pi$

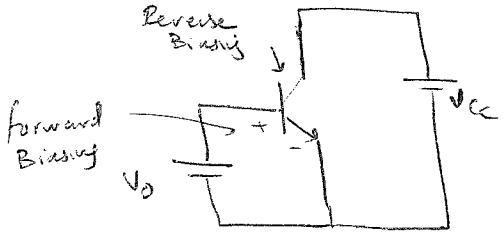
$\simeq \beta r_o$

lect-24

To-day's lect:

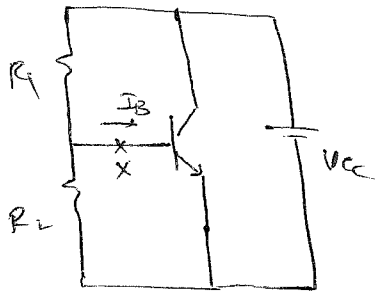
- Simple Biasing Techniques:

Introduction of Biasing:-



- How to create ($V_D \cong 0.8V$) without Battery from V_{cc}

* We can do that using Voltage divide.



$$V_X \cong \frac{R_2}{R_2+R_1} V_{cc}$$

that gives the voltage that we need.

Questions:

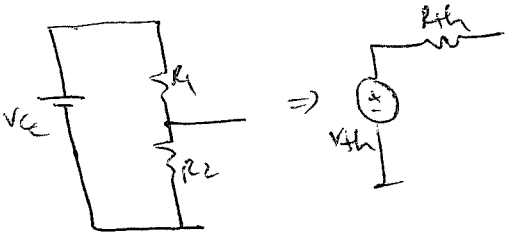
1) what happens to the input impedance ?

$$R_{in} = r_\pi \| R_1 \| R_2$$

So we see that R_{in} is reduced to maximum $R_{in} = r_\pi$, $\Rightarrow (R_1$ and $R_2)$ should be prefectely much greater than r_π.

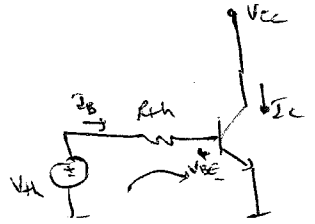
(2) How about the base current ?

Using Thevenin equivalent circuit



$$V_{th} = \frac{R_2}{R_2+R_1} V_{cc}$$

$$R_{th} = R_1 \| R_2$$



KVL:

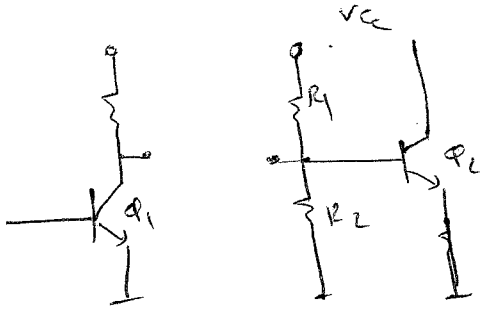
$$V_{th} = R_{th} I_B + V_{BE}$$

$$= R_{th} I_B + V_T \ln \frac{I_C}{I_S}$$

$$= I_B R_{th} + V_T \ln\left(\frac{\beta I_B}{I_S}\right)$$

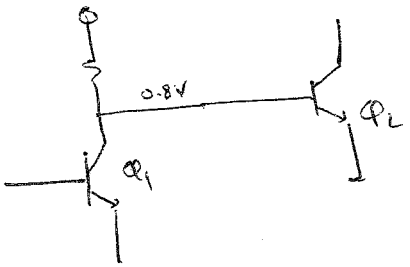
④ To reduce sensivity of V_X to I_B and β
choose $\frac{V_{CC}}{R_1+R_2} \gg I_B$.

③ How do we interface this circuit with the preceding stage?

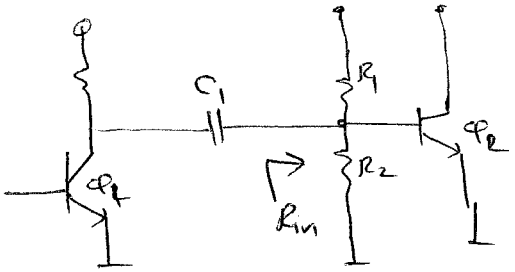


that can be done by

1) design preceding stage for $V_{out} \simeq 0.8V$ and connect directely (dc coupling)
So in that case we don't need R_1, R_2



2) Using ac coupling



How to choose C_1
C_1 must be large because $Z_{C_1} = \frac{1}{C_1 \omega}$
C_1 should be reasonable short circuit at the lowest signal frequency.

* $\frac{1}{C_1 \omega} \ll R_{in} \left(= (r_\pi \| R_1 \| R_2)\right)$

⊛ Design Procedure for Simple Biasing

$$I_C \longrightarrow I_B \longrightarrow \frac{V_{CC}}{R_1+R_2} \cong 10\, I_B \longrightarrow (1)$$

$$\frac{R_2}{R_1+R_2} V_{CC} \cong 0.8V \longrightarrow (2)$$

From (1, 2) we can determine R_1 / R_2.

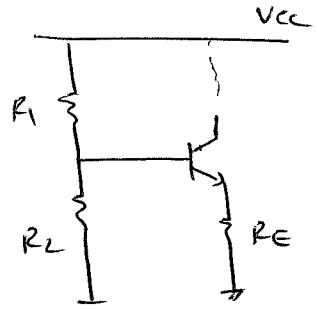
⊛ Problem of Supply Sensitivity:-

* Suppose V_{CC} ↑ by 5% ⇒ that means V_{BE} ↑ by 5%.

If $V_{BE} = 800mV$ ⇒ 5% then $\Delta V_{BE} = 40mV$

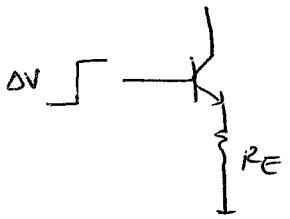
I_C ↑ by $\exp\left(\frac{40mV}{26mV}\right) = 4.65$ fold. (huge) ⇒ that is Problem

To Solve that, we use CE stage with degeneration



* Observation :- If V_{BE} ↑

⇒ I_C ↑ ⇒ I_E ↑ ⇒ V_{RE} ↑



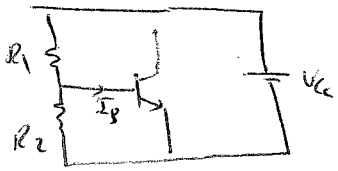
Today's lect.

- Supply sensitivity in CE stage with Deg
- Design Example
- Self Biased stage

Review

* Simple Biasing

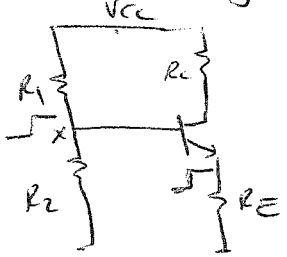


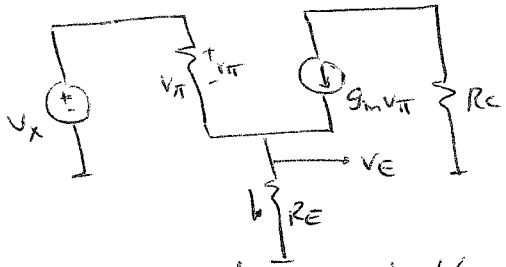


$V_{cc}\frac{R_2}{R_1+R_2} \gg I_B$.

* Supply sensitivity:

5% change in V_{cc} ⟶ 4.65X change in I_c





for a given change of V_x, we need how much the V_E change.

$$i_c = \frac{V_E}{R_E}$$

KVL: $V_x = V_\pi + V_E \Rightarrow V_\pi = V_x - V_E$

KCL @ E: $\frac{V_x - V_E}{r_\pi} + g_m\left[\frac{V_x - V_E}{\text{xxx}}\right] = \frac{V_E}{R_E}$

$$V_x\left(\frac{1}{r_\pi} + g_m\right) = V_E\left(\frac{1}{R_E} + \frac{1}{r_\pi} + g_m\right)$$

$$\frac{V_E}{V_x} = \frac{R_E}{1/g_m + R_E} < 1 \qquad g_m r_\pi = \beta,\ \beta+1 \cong \beta$$

if $1/g_m \ll R_E$

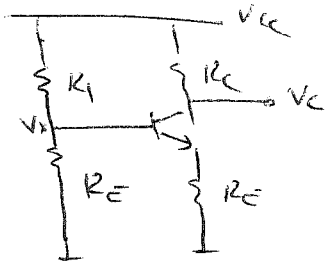
$\frac{V_E}{V_x} = 1$ that means changing of V_x will create change in V_E by the same amount.

⇒ V_{BE} changes by small amount.

$\frac{1}{g_m} << R_E \Rightarrow \boxed{R_E I_C >> V_T}$

$\Rightarrow$ In this case the base current remain the same.

* Summery of Biasing:



① $\frac{V_{CC}}{R_1+R_2} \gg \cong 10 I_B$.

② $R_E I_C$ must be (much) greater than V_T

③ $V_C = V_{CC} - I_C R_C \geq V_X$

Example: $V_{CC} = 1.5V$, $P = 1.5mW$, $\beta = 100$, Desig the circuit

$I_{supply} = I_{CC} = \frac{P}{V_{CC}} = 1mA \Rightarrow I_C = 1mA$

$I_B = 10\mu A \Rightarrow \boxed{\frac{V_{CC}}{R_1+R_2} = 10 I_B = 100\mu A} \rightarrow ①$

$R_E I_C >> V_T$

Pick $R_E I_C = 100mV \Rightarrow \boxed{R_E = 100\Omega}$

$V_{BE} = 800mV$

$V_X = V_{BE} + V_E = \boxed{900mV = \frac{V_{CC}}{R_1+R_2} \times R_2} \rightarrow ②$

Solving (1,2) $\Rightarrow \boxed{R_1 = 9k\Omega}$, $\boxed{R_2 = 6k\Omega}$

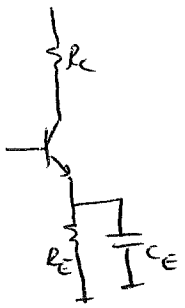
$V_C = V_{CC} - I_C R_C \geq V_X = 900mV \Rightarrow \boxed{R_C = 600\Omega}$

Quiz:

a) Calculate the gain of the amplifier

b) How do we increase the gain without changing the Bias Compone

a) $A_v = -\frac{R_C}{\frac{1}{g_m} + R_E} = -4.76$



b) We can increase A_v by decrease R_E

that can be done by connect C_E // R_E

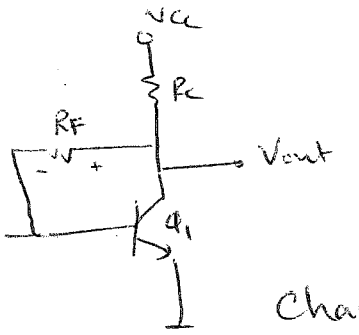
$\Rightarrow A_v = \frac{-R_C}{\frac{1}{g_m}} = -g_m R_C$

$\frac{1}{C_E}$ should be small

$V_x = 45mV$ (5% change)

$V_E = \frac{R_E}{1/g_m + R_E} \times 45mV = 36mV$ (Change in Emitter (Collector) current $= \frac{36mV}{100\Omega} = 0.36mA$.

* Self Biased CE stage :-



① If V_{cc} change by 5%)
⇒ V_C change by 5%
⇒ V_B change by 5%
⇒ I_B increasing, I_C increasing
⇒ V_{out} decrease.

Changes in V_{cc} are counteracted by Q_1

② $V_B = V_C - I_B R_F$
⇒ Q_1 doesn't saturate

Calculate the collector bias current :-

Since $\beta >> 1 \Rightarrow I_B << I_C$

$V_C = V_{cc} - I_C R_C$

$V_{cc} - I_C R_C - R_F I_B = V_{BE}$ if V_{BE} is given

$V_{cc} - I_C R_C - R_F \frac{I_C}{\beta} = V_{BE} \Rightarrow I_C$

① $I_C = \frac{V_{cc} - V_{BE}}{R_C + R_F/\beta}$

To minimize sensitivity to β, we choose $R_C >> \frac{R_F}{\beta}$

$\Rightarrow R_F << \beta R_C$

② If V_{cc} goes up by 5%, what happen to collector current.

$\Rightarrow I_C \uparrow$ by 5%.

Example: $V_{cc} = 1.5V$, $I_C = 1mA$, $\beta = 100$, $P = 1.5mW$

$V_C \cong 0.9V \Rightarrow R_C = \frac{V_{cc} - 0.9}{1mA} = 600\Omega$

$R_F = \frac{\beta R_C}{100} \Rightarrow R_F = 6k\Omega$

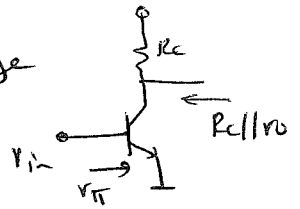
$I_B = 10\mu A$ Drop on $R_F = 60mV$

Today's lect

- Common Base Stage
- Basic properties
- Bias Design

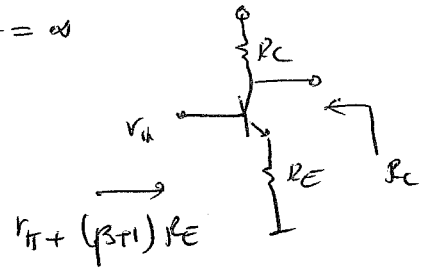
Review:

- CE stage



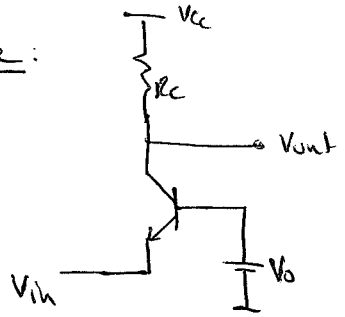
$$A_v = -g_m(R_C \| r_o)$$

for $V_A = \infty$



$$A_v = -\frac{R_C}{1/g_m + R_E}$$

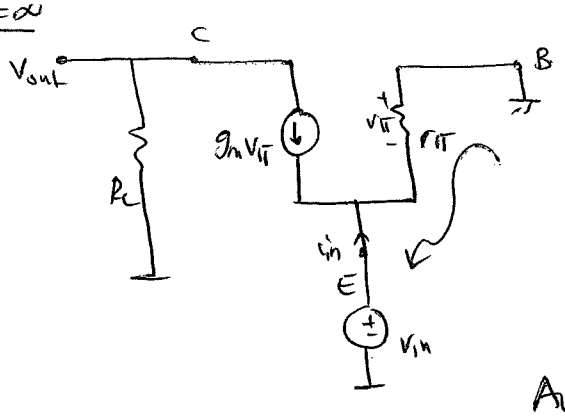
* CB stage:



for CB stage, the input is applied to the emitter and the output is taken at the collector.

Calculate A_v, R_{in}, R_{out}

$V_A = \infty$



KVL: $V_\pi + V_{in} = 0$

$$V_\pi = -v_{in}$$

$$v_{out} = -g_m V_\pi R_C$$

$$v_{out} = g_m v_{in} R_C$$

$$A_v = \frac{v_{out}}{v_{in}} = g_m R_C$$

* There isn't any phase.

Calculate $R_{in} = \frac{v_{in}}{i_{in}}$

KCL @ node E

$i_{in} = -V_\pi \left[g_m + \frac{1}{r_\pi} \right]$

$$i_{in} + g_m V_\pi + \frac{V_\pi}{r_\pi} = 0 \Rightarrow i_{in} = v_{in} \left(g_m + \frac{1}{r_\pi} \right)$$

$$\Rightarrow i_{in} = v_{in} \left[\frac{g_m r_\pi + 1}{r_\pi} \right] \cong v_{in}\, g_m$$

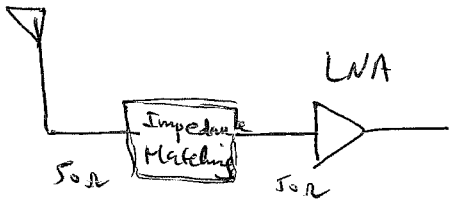
$$\Rightarrow \boxed{R_{in} = \frac{v_{in}}{i_{in}} = \frac{1}{g_m}}$$

It is small number

R_{in} ⟶ small

Application of CB:

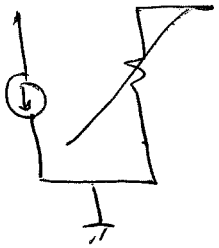
- Antenna - LNA Interface

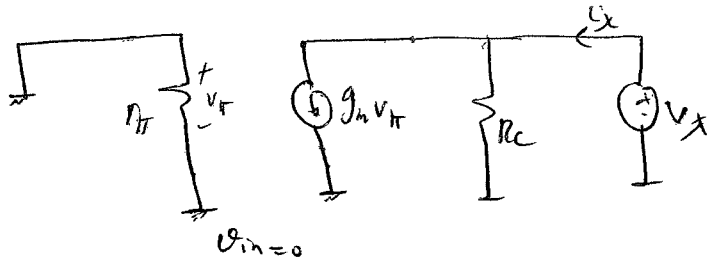


CB can be used as amplifier with low input impedance

$\Rightarrow R_{in}|_{LNA} = R_{antenna}$

* Calculate R_{out}





$V_\pi = 0$

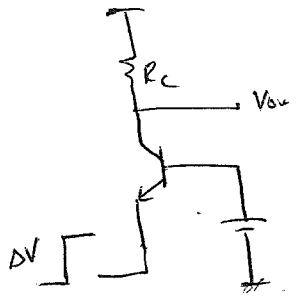
$g_m V_\pi = 0$ (open circuit)

$$\Rightarrow \boxed{R_{out} = R_c}$$

Diff between CS and CB

	CS	CB
R_{in}	r_π	$1/g_m$
A_v	$-g_m R_c$	$g_m R_c$

Question: Why doesn't the CB stage invert?



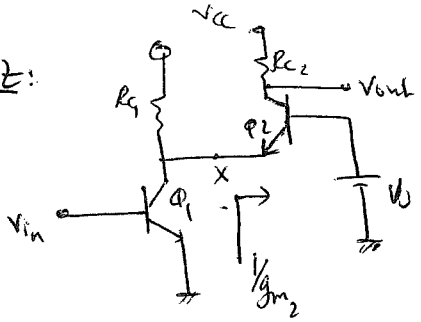
when V_{in} is change from Low to high

$\Rightarrow V_{BE} \downarrow \Rightarrow I_C \downarrow$

$V_C = V_{CC} - I_C R_C \Rightarrow V_C \uparrow$ goes up.

$\Rightarrow$ so no inversion

Quiz:



find $A_v = \frac{v_{out}}{v_{in}}$

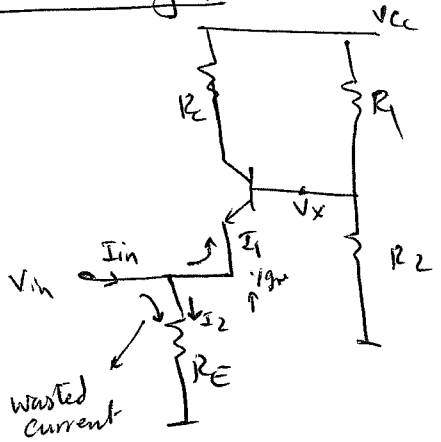
$$\frac{V_{out}}{v_{in}} = \frac{v_x}{v_{in}} * \frac{V_{out}}{V_x}$$

$$\frac{v_x}{v_{in}} = -g_{m_1}\left[R_{C_1} \| 1/g_{m_2}\right]$$

$$\frac{V_{out}}{V_x} = g_{m_2} R_{C_2}$$

$$A_v = -g_{m_1} g_{m_2} \left(R_{C_1} \| 1/g_{m_2}\right) R_{C_2}$$

* Bias Design



- DC current conduction

It is possible by,



$$I_1 = \frac{R_E}{R_E + 1/g_m} I_{in}$$

, inorder to reduce the waste current

$R_E \gg 1/g_m$

Example:

$V_{CC} = 1.5V \quad P = 1.5mW \;,\; \beta = 100$

$\Rightarrow I_C \doteq 1mA$ select $1/g_m = 26\Omega$, $R_E \cong 10\, 1/g_m = 260\Omega$

$V_E = 260mV$

$V_X = V_{BE} + V_E = 1.06\,V$

$$\left.\begin{aligned} \frac{V_{CC}}{R_1+R_2} = \frac{I_C}{\beta} = 100\mu A \\ \frac{R_2}{R_1+R_2} V_{CC} = 1.06\,V \end{aligned}\right] \Rightarrow \begin{aligned} R_1 &= 10.6k\Omega \\ R_2 &= 4.4k\Omega \end{aligned}$$

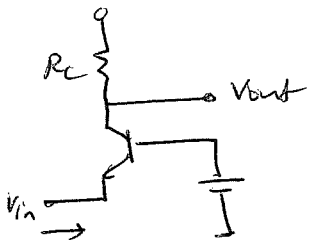
Choose $V_C \geq V_X$ inorder to keep transistor in active $\quad V_{CC} - R_C I_C \geq 1.06 \Rightarrow R_C = 440\Omega$

Today's fact.

- Emitter Follower Topology
- Basic Properties

Review:

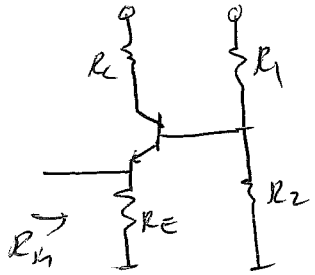
CB Topology



$A_v = g_m R_C$

$R_{in} = 1/g_m$

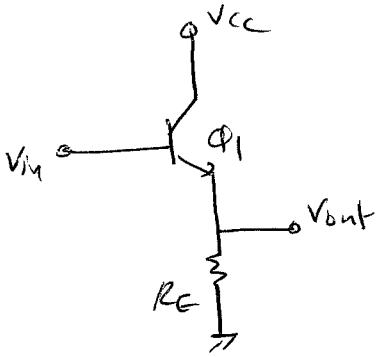
Bias Design



$R_E \gg 1/g_m$

$R_{in} = 1/g_m \,//\, R_E$

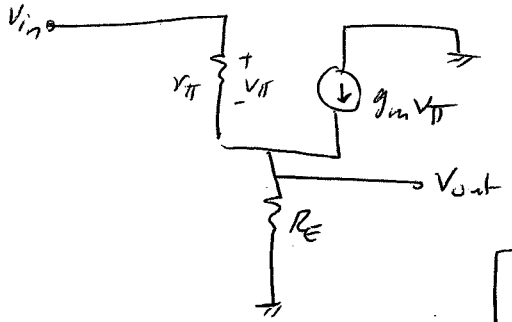
Emitter Follower – Common Collector



input is applied to the Base and the output is taken at the emitter.

Assume $V_A = \infty$

Calculate A_v



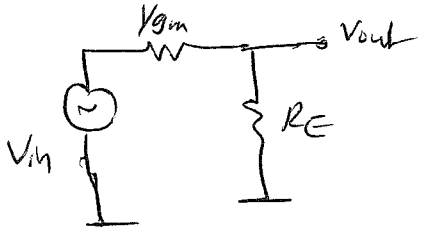
$V_\pi = V_{in} - V_{out}$

$\frac{V_{in} - V_o}{r_\pi} + g_m(V_{in} - V_{out}) = \frac{V_{ov}}{R}$

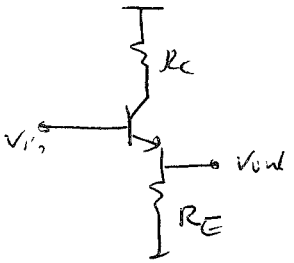
$A_v = \frac{\text{Resistance tied between E and GND}}{1/g_m + \text{resistance tied between E and GND}}$

$$\frac{V_{out}}{V_{in}} = \frac{R_E}{1/g_m + R_E}$$

We can assume that the voltage gain is expressed as voltage divider



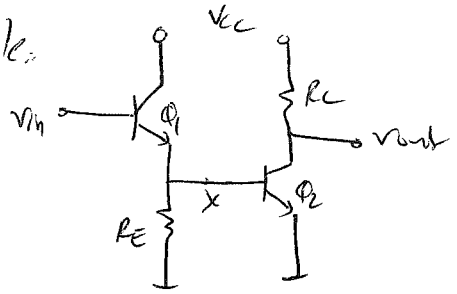
Question: Do these result change if we insert resistor in the collector?



The result isn't change.

$$A_v = \frac{R_E}{1/g_m + R_E}$$

Example:



Cascade of two stage

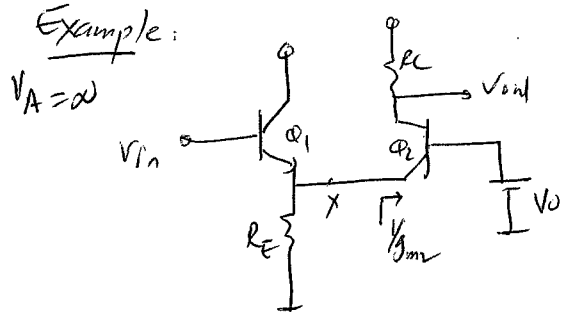
$$\frac{V_X}{V_{in}} = \frac{R_E \parallel r_{\pi 2}}{1/g_{m_1} + R_E \parallel r_{\pi 2}}$$

$$\frac{V_{out}}{V_X} = -g_{m_2} R_C$$

$$A_v = \frac{V_X}{V_{in}} \times \frac{V_{out}}{V_X} = -\frac{R_E \parallel r_{\pi 2}}{1/g_{m_1} + R_E \parallel r_{\pi 2}} \times (g_{m_2} R_C)$$

Example:

$V_A = \infty$

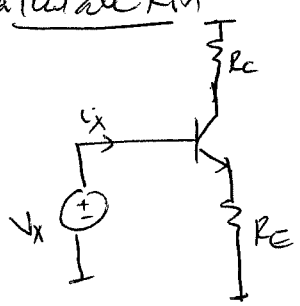


$$\frac{V_X}{V_{in}} = \frac{R_E \parallel 1/g_{m_2}}{1/g_{m_1} + R_E \parallel 1/g_{m_2}}$$

$$\frac{V_{out}}{V_X} = g_{m_2} R_C$$

$$A_v = \frac{(R_E \parallel 1/g_{m_2})\, g_{m_2} R_C}{1/g_{m_1} + R_E \parallel 1/g_{m_2}}$$

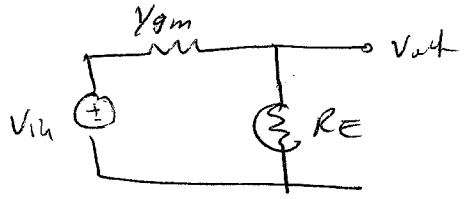
Calculate R_{in}



Since R_C isn't effect the voltage gain the circuit becomes as the emitter degeneration

$$R_{in} = r_\pi + (\beta + 1) R_E$$

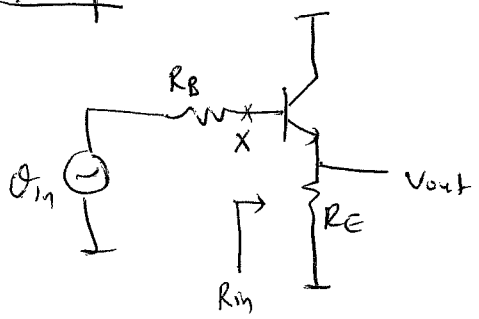
R_{out}



when $v_{in} = 0$

$R_{out} = R_E \,||\, 1/g_m$

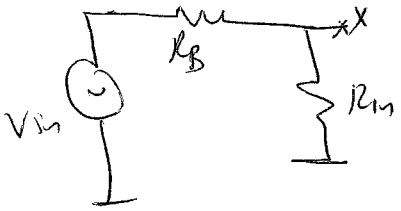
Example



Find A_v, R_{in}, R_{out}

$$\frac{V_X}{V_{in}} = \frac{R_{in}}{R_B + R_{in}} \qquad R_{in} = r_\pi + (\beta+1)R_E$$

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



$$\frac{V_{out}}{V_X} = \frac{R_E}{\frac{1}{g_m} + R_E}$$

$$A_v = \frac{r_\pi + (\beta+1)R_E}{r_\pi + (\beta+1)R_E + R_B} * \frac{R_E}{1/g_m + R_E}$$

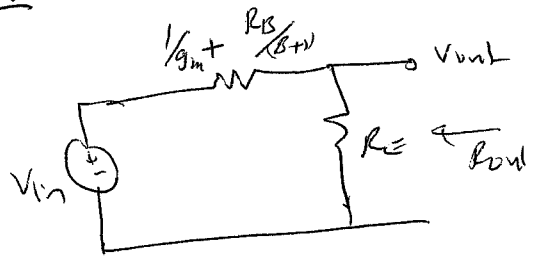
$(\beta+1)$ بالمقام

$$= \frac{\frac{1}{g_m} + R_E}{\frac{1}{g_m} + R_E + \frac{R_B}{\beta+1}} * \frac{R_E}{\frac{1}{g_m} + R_E}$$

$$\boxed{A_v = \frac{R_E}{\frac{1}{g_m} + R_E + \frac{R_B}{\beta+1}}}$$

$$\Rightarrow R_{in} = R_B + r_\pi + (\beta+1)R_E$$

R_{out}



when $v_{in} = 0$

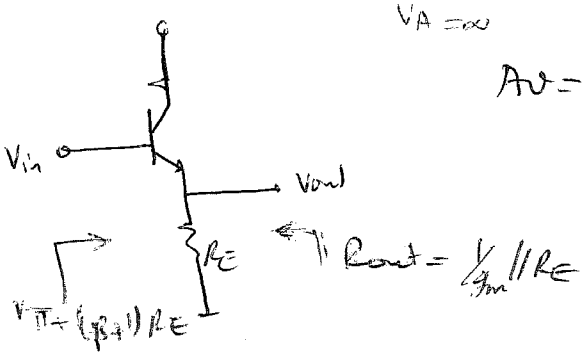
$$R_{out} = R_E \,||\, \left(\frac{1}{g_m} + \frac{R_B}{\beta+1}\right)$$

lect 28

Today's lect.

- Emitter Follower as a buffer
- Bias Design
- Summery of Bipolar Circuit.

Review: Emitter follower



$$A_v = \frac{R_E}{R_E + 1/g_m}$$

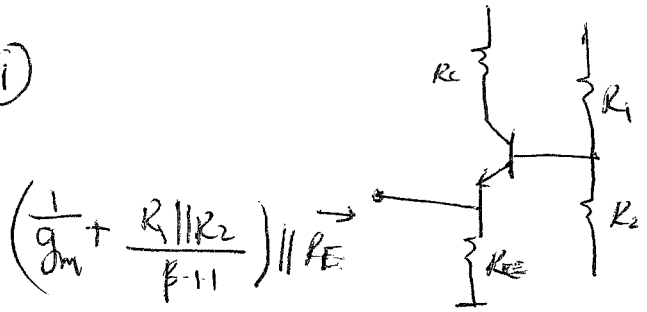
Emitter follower with base resistance

$$A_v = \frac{R_E}{R_E + 1/g_m + \frac{R_B}{\beta+1}}$$

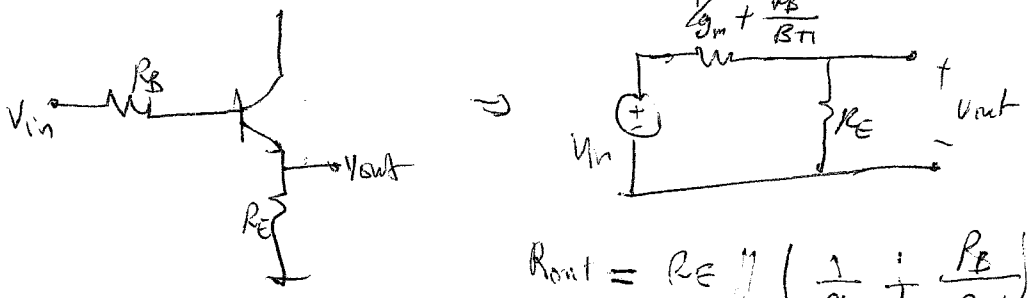
$$R_{out} = R_E \,//\, \left(1/g_m + \frac{R_B}{\beta+1}\right)$$

* Two Remarks :-

(1)

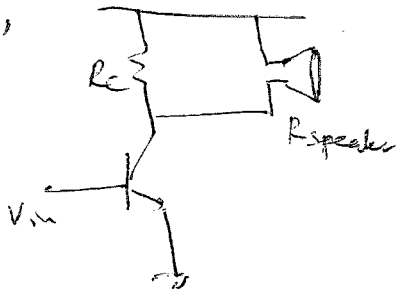


(2)



$$R_{out} = R_E \,//\, \left(\frac{1}{g_m} + \frac{R_B}{\beta+1}\right)$$

- Emitter follower as a buffer

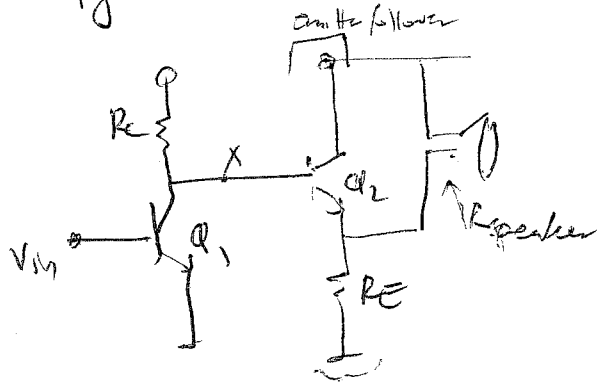


$A_V = -g_m(R_c \| R_{speaker})$

ex $R_c = 1k$, $R_{sp} = 8\Omega$

$A_{V2} = -g_m(8\Omega)$

Modify the circuit to be as $V_A = \infty$



$$\frac{V_X}{V_{in}} = -g_{m1}\left(R_c \| r_\pi + (\beta+1)(R_E \| R_{sp}\right)$$

$\beta = 100$ $R_E = 500\Omega$

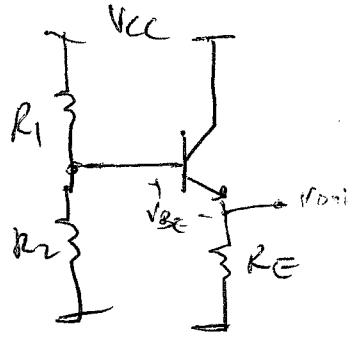
$$\frac{V_X}{V_{in}} = -g_m(8k\Omega) = A_{V1}$$

$$\Rightarrow \frac{V_{out}}{V_X} = \frac{R_E \| R_{speaker}}{R_E \| R_{speaker} + 1/g_m} = A_{V2}$$

$\Rightarrow A_V = A_{V1} \times A_{V2} \Rightarrow$ the gain is better gain

$\Rightarrow$ the emitter follower has buffer ability.

* Bias Design:



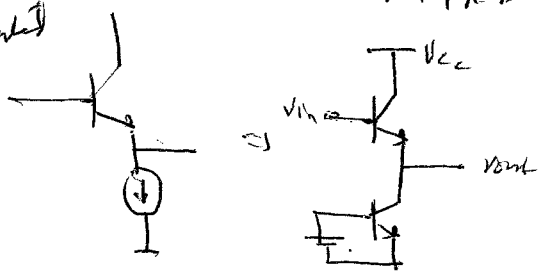
In this case in all time Vc is connected to Vcc and $V_B < V_E \Rightarrow$ Q isn't go to saturated forever.

To design

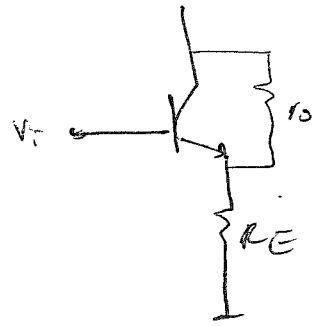
$$V_{out} = \frac{V_{cc} - V_{BE}}{2} = V_{RE}$$

$$\frac{V_{cc}}{R_1 + R_2} \cong 10\, I_B$$

In Integrated Circuit



Emitter follower when $V_A \neq \infty$



in ac model

$r_o \,//\, R_E$

so $A_v = \dfrac{R_E // r_o}{R_E // r_o + 1/g_m}$

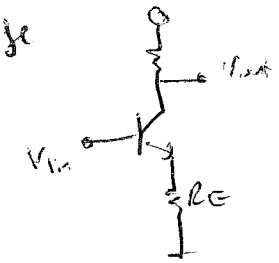
$R_{in} = r_{\pi} + (\beta+1)(R_E // r_o)$

$R_{out} = 1/g_m \,//\, (R_E // r_o)$

Summary of BJT

CE stage

$V_A = \infty$

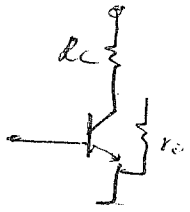


$A_v = -\dfrac{R_C}{\frac{1}{g_m} + R_E}$

$R_{in} = r_{\pi} + (\beta+1) R_E$

$R_{out} = R_C$

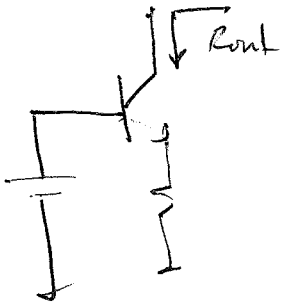
$V_A \neq \infty$



$A_v = -g_m(R_C // r_o)$

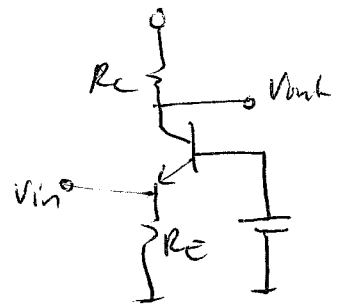
$R_{in} = r_{\pi}$

$R_{out} = R_C // r_o$



$R_{out} = (1 + g_m r_o)(R_E // r_{\pi}) + r_o$

Common Base Stage



$V_A = \infty$

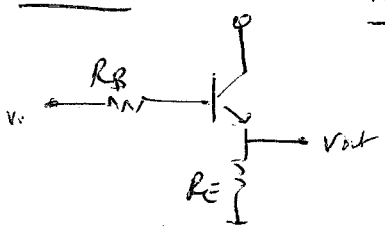
$A_v = g_m R_C$

$R_{in} = 1/g_m \,//\, R_E$

$R_{out} = R_C$

Follower

$V_A = \infty$

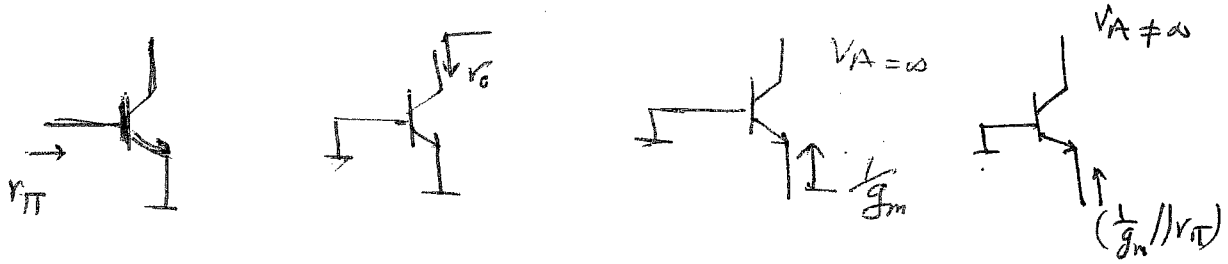


$A_v = \dfrac{R_E}{R_E + \frac{1}{g_m} + \frac{R_B}{\beta+1}}$

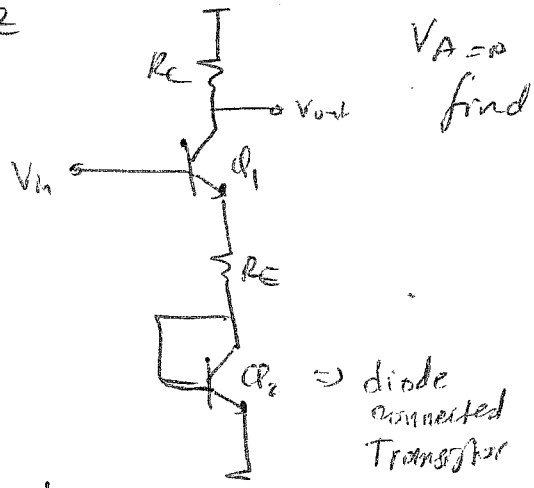
$R_{in} = R_B // r_{\pi} + (\beta+1) R_E$

$R_{out} = \left[\left(\frac{R_B}{\beta+1}\right) + \frac{1}{g_m}\right] // R_E$

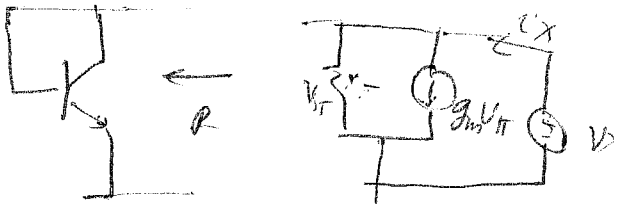
Usfel Impedance Expression



Quiz



$V_A = \infty$ find A_v

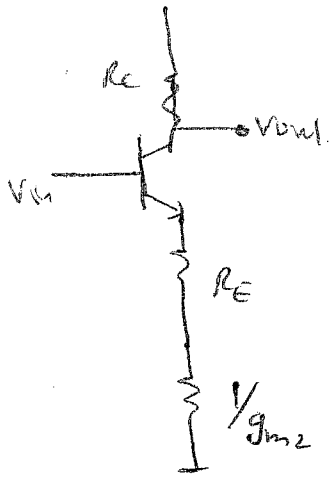


$V_\pi = V_x$

$i_x = \frac{V_x}{r_\pi} + g_m V_x$

$i_x = V_x\left(\frac{1}{r_\pi} + g_m\right) =$

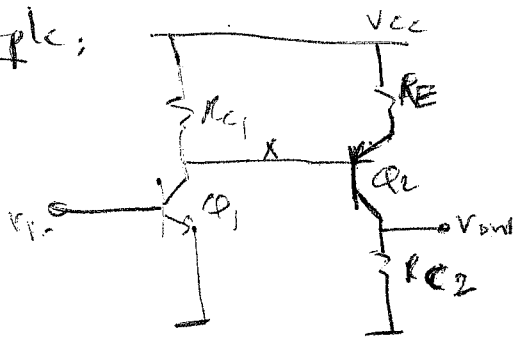
$$\frac{V_x}{i_x} = \frac{1}{g_m}$$



$$A_v = -\frac{R_C}{\frac{1}{g_{m_1}} + R_E + \frac{1}{g_{m_2}}}$$

$V_A = \infty$

Example:



$$\frac{V_x}{V_{in}} = -g_{m_1}\left[R_{C_1} \parallel \left(r_{\pi_2} + (\beta+1)R_E\right)\right]$$

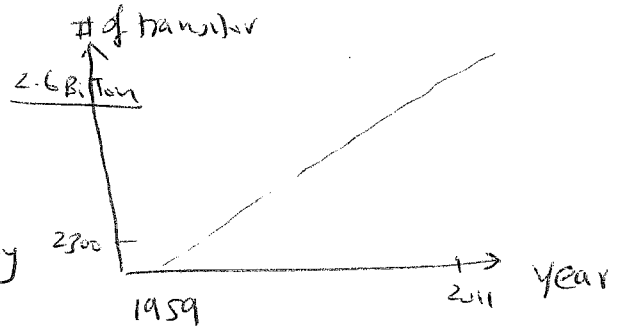
$$\frac{V_{out}}{V_x} = -g_{m_2}\frac{R_{C_2}}{R_E + \frac{1}{g_{m_2}}}$$

Chapter 6

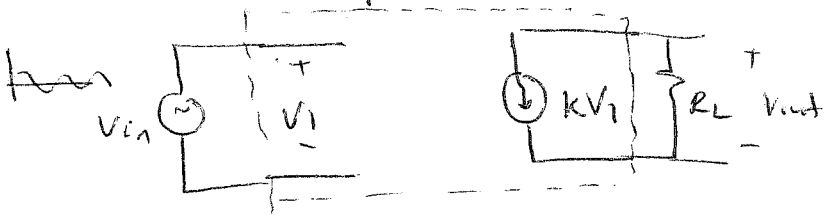
Physics of MOS Transistor

Today's lect
- Structure of MOSFET
- Basic operation of MOSFET

Gorden More Law
of components (transistor) per chip was doupling every 18 month



- Lets build an amplifier:-

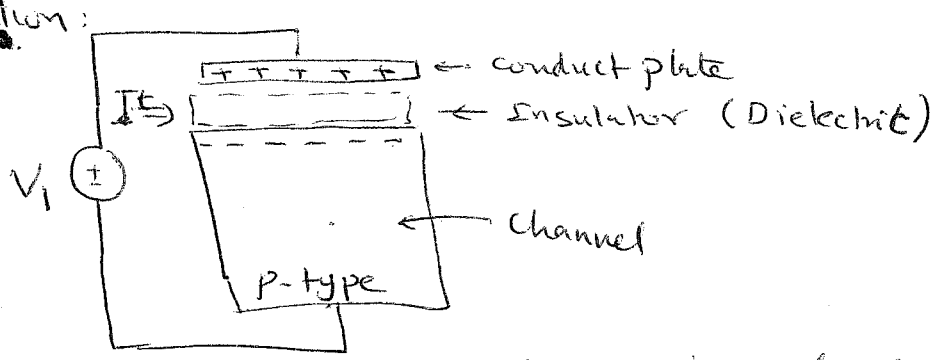


$V_{out} = -R_L k V_1$

$= -R_L k V_{in}$

$A_v = -R_L k$

- Observation:



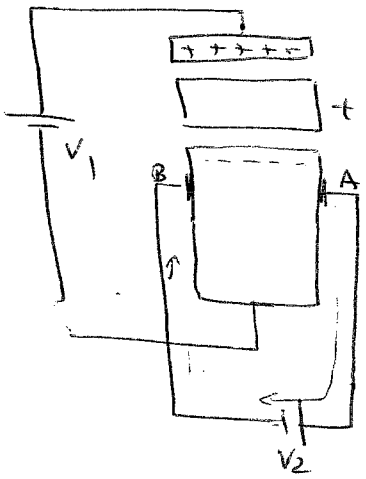
- The positive charge attack the negative charge
- A channel is created
- The charge which stored by a capacitor

$$Q = CV_1$$

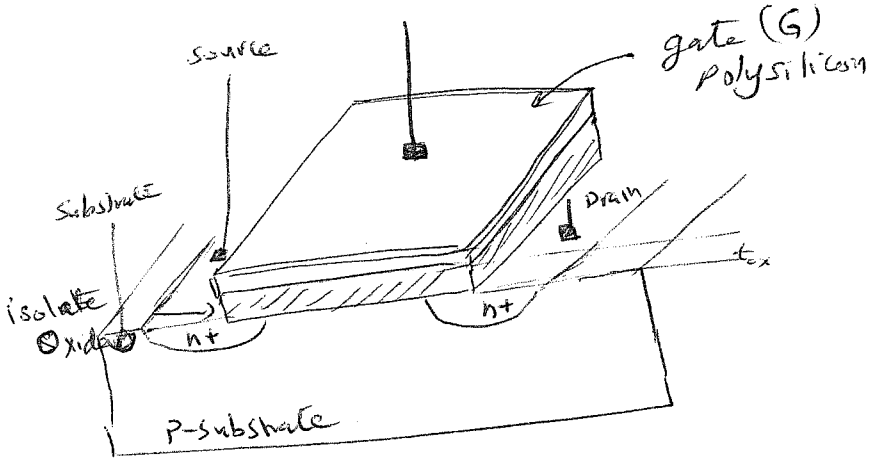
(a) - If V_1 increases Q_1 increases
⇒ the electron density in p-type increases

(b) If the insulator distance (thikness) decreases the capacitance increases
⇒ Q increases ⇒ electron density in the channel increases.
⇒ the density of electron increases by ↑

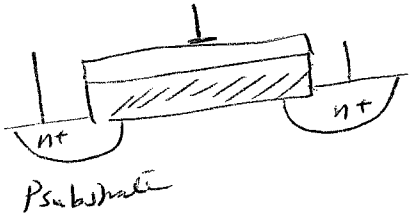
- Now, If we apply V_2 at the ~~end~~ themends of the Channel as shown.
  Current flows from A to B
- If V_1 increases, the electron density increases, the resistance between A,B decreases ⇒ the current between A,B increases.
  ⇒ that means, the voltage V_1 control the current between (A,B)
  ⇒ Voltage controlled current source

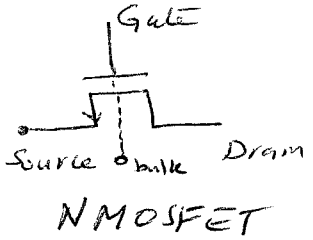


Structure of MOSFET:- (metal oxide semiconductor)



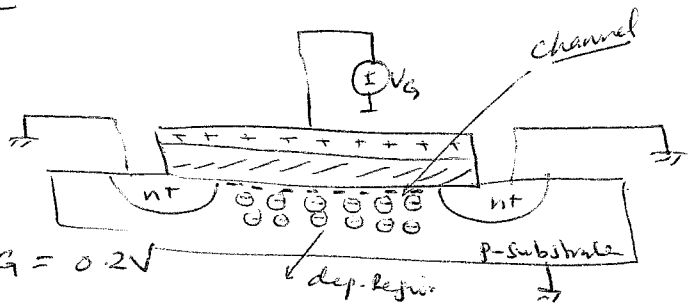
1) The MOSFET (MOS) Field Effect transistor has four therminels (gate - source - drain - substrate (bulk))
2) MOS structure is symmetric (source - Drain)
3) t_{ox} decrease by technology (15 - 18 A°)

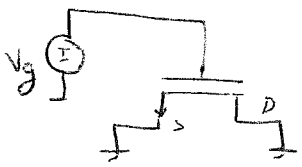




NMOSFET

MOS Operation





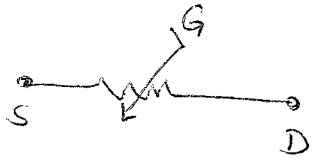
- If $V_G = 0.2V$

$V_G = 0.2V$

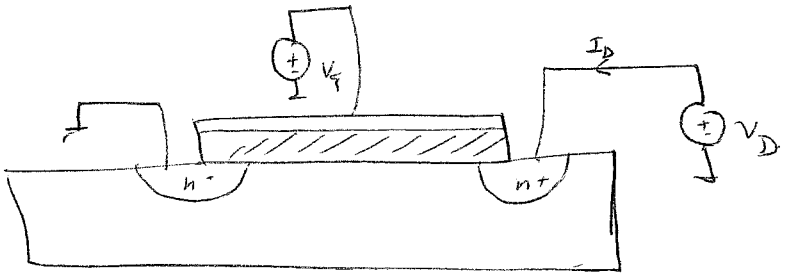
- When we apply ⊕ voltage V_G ⇒ the hole is repuled out and ~~left positive~~ negative ions (depletion region is created)

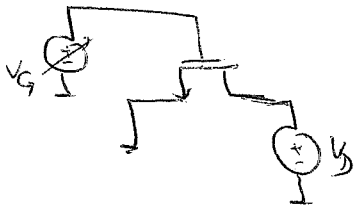
- After V_G reach V_{Th} threshold Region, we get some electron in the channel.

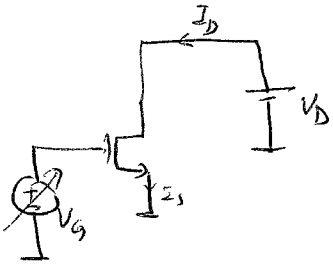
- As V_G increase, electron density in the channel increases
⇒ The resistance between the source and Drain decrease.



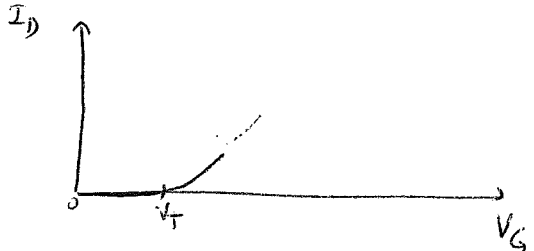
- Assume $V_D > V_S = 0$







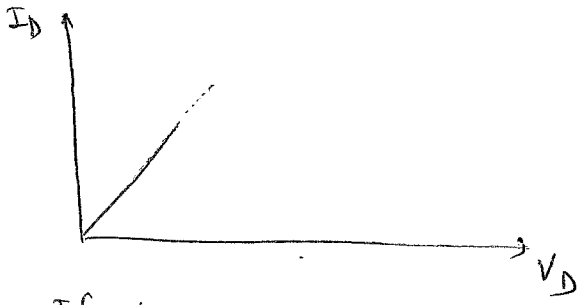
① Assume V_D is constant $V_D = 0.3V$

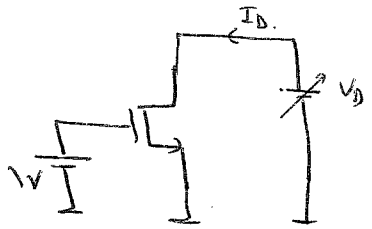


If $V_G = 0$, no channel
No current flow $I_D = 0$

If $V_G = V_T$, Channel created , current flow between D and Sorce
$I_D = I_S$, because the isulation $I_G = 0$

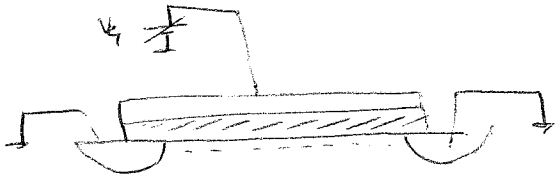
② Assume V_G = cts and $V_G = 1V$ and V_D is variable





- If $V_D = 0 \Rightarrow I_D = 0$
- As $V_D \nearrow$, $I_D \nearrow$

• Behavior of Channel.



Case 1: $V_{GS} > V_{th}$, $V_S = V_D = 0$.

Channel is created and MOS is turn, but no has current.

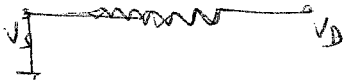
$Q = CV \Rightarrow$ the electron density are the same at each pts.

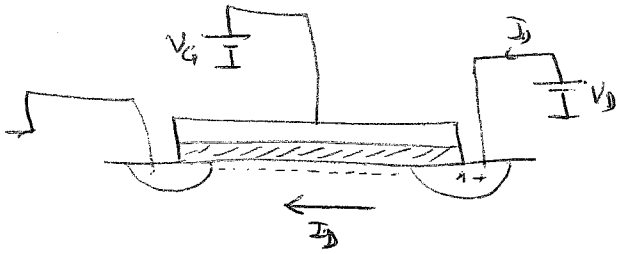
Case 2:

$V_{GS} > V_{th}$, $V_S = 0$, $V_D > 0$

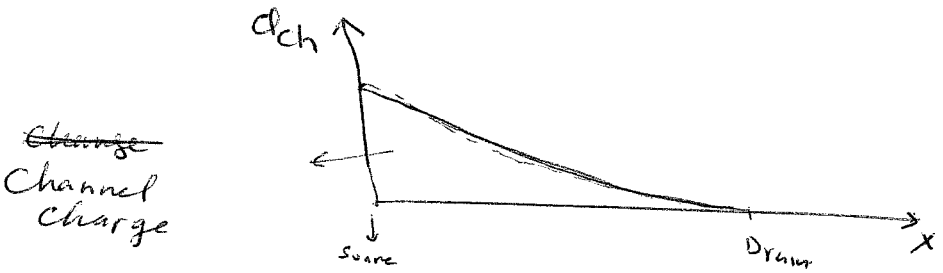
I_D will flow

I_D will flow through resistive path the voltage is varies through the Channel.





- Voltage along the Channel increases as we go from source to Drain ⇒ the electron density is varying through the Channel.

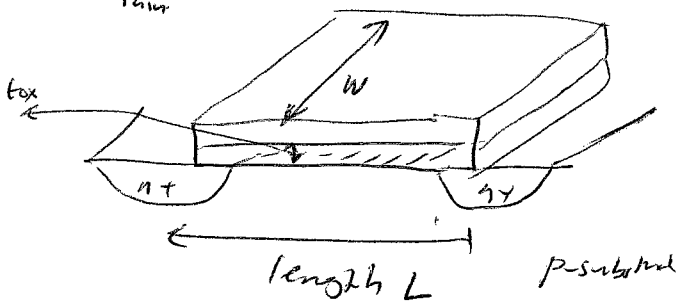


• Dimensions of MOS

Length (Drawn L_{drawn}, L_{eff})

Width

t_{ox} : oxide thickness



• Derivation of I/V Characteristics:

① Channel charge density:

Case 1: $V_{GS} > V_{th}$, $V_D = 0$

$$Q_{ch} = \underbrace{WL}_{\text{Total Area}} \cdot C_{ox} \cdot \underbrace{(V_{GS} - V_{th})}_{\text{overdrive voltage}}$$

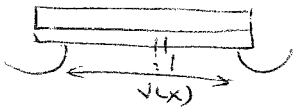
C_{ox}: Capacitance / unit Area

$$Q_{ch_{density}} = W C_{ox} (V_{GS} - V_{th}) \quad \text{Coulomb/m}$$

Case 2: $V_{GS} > V_{th}$, $V_D > 0$

@ index:

$$Q_{ch_{density}} = W C_{ox} (V_{gs} - V_{th} - V(x))$$



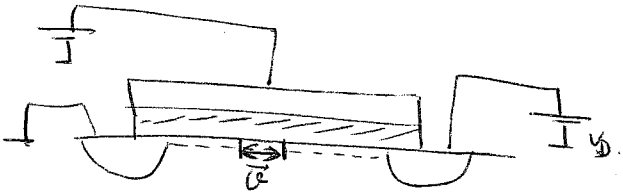
② Drain Current:

$$v = \mu E$$

velocity — mobility — Electric field.

$$E = -\frac{dV}{dx}$$

$$\Rightarrow v = -\mu \frac{dV}{dx}$$



total charge in length dx

$$= v * Q_{ch_{density}}$$

$$I_D = -v \cdot W C_{ox} [V_{GS} - V_{th} - V(x)]$$

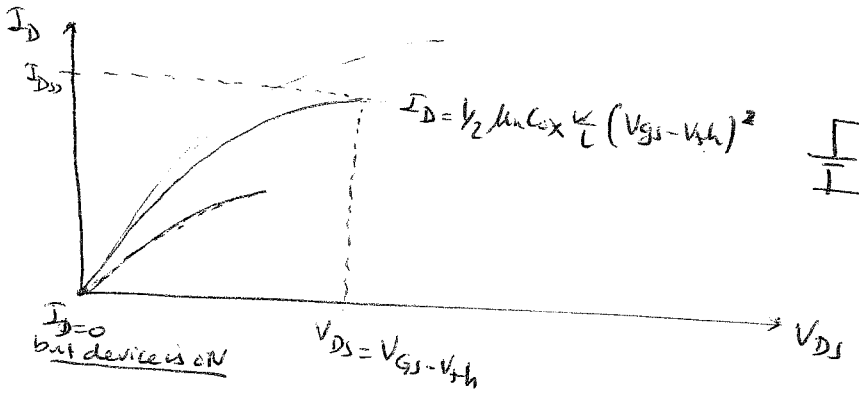
$$= +\mu_n \frac{dV}{dx} W C_{ox} (V_{gs} - V_{th} - V(x))$$

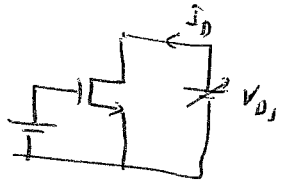
$$\int_0^L I_D \, dx = \int_0^{V_{DS}} \mu_n W C_{ox} (V_{gs} - V_{th} - V(x)) \, dV$$

$$L I_D = \mu_n C_{ox} W \left[(V_{gs} - V_{th}) V - \frac{1}{2} V^2 \right]_0^{V_{DS}}$$

$$I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{gs} - V_{th}) V_{DS} - \frac{1}{2} V_{DS}^2 \right] \quad V_{GS} > V_{th}$$

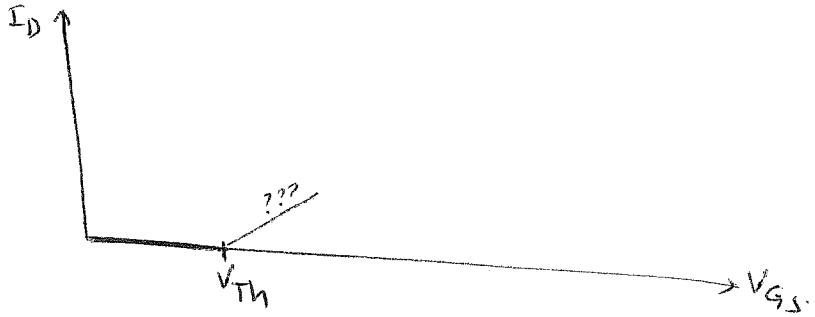
Assume $V_{gs} = cts$





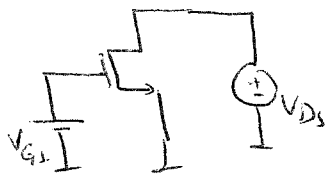
$$I_{D_{max}} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{gs}-V_{th})^2$$

Keep $V_{DS} = cts$

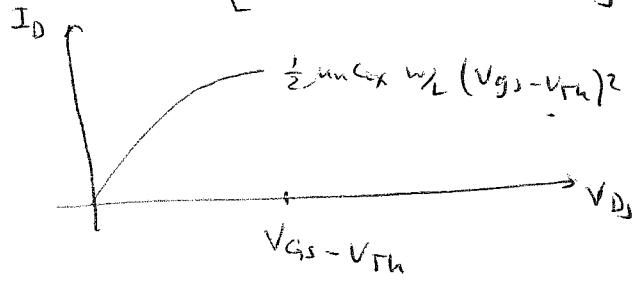


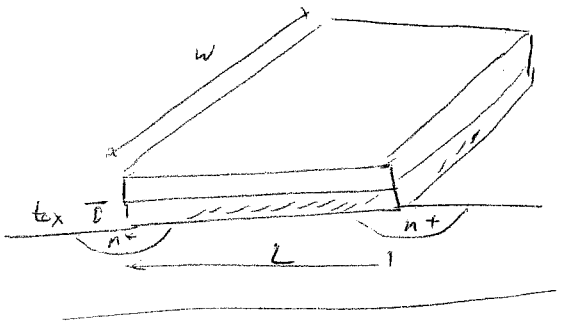
Today's lect.
- MOS I/V characteristics
- Region of operation
- Simple MOS Model

Review



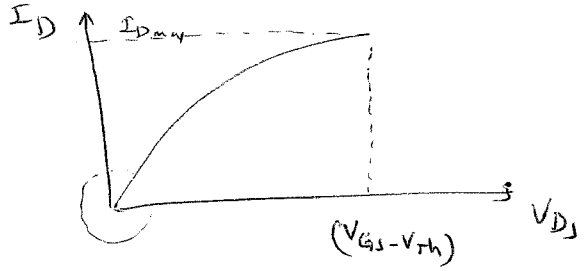
$$I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS}-V_{TH}) - \tfrac{1}{2}V_{DS}^2\right]$$





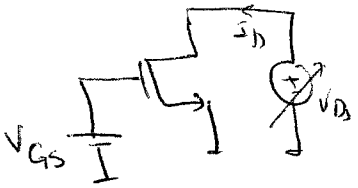
- I/V Charact

$$I_D = \tfrac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{GS}-V_{TH})^2$$



If $V_{DS} << 2(V_{GS}-V_{TH})$ $\Rightarrow$ $I_D \cong \mu_n C_{ox} \frac{W}{L}(V_{GS}-V_{TH})V_{DS}$

If we assume $(V_{GS}-V_{TH})$ is constant



$I_D \propto V_{DS}$ $\Rightarrow$ resistive Relation

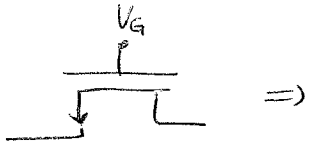
$$I_D = \underbrace{\mu_n C_{ox} W/L (V_{GS}-V_{TH})}_{\text{slope}} V_{DS}$$

$$R_{ON} = \frac{1}{\mu_n C_{ox} W/L (V_{GS}-V_{TH})}$$ $\Rightarrow$ MOS acts as resistance

R_{ON} : is a tunable resistance
its value is depends on $(V_{GS} - V_{th})$

⇒ MOS can acts as a voltage dep resistance if $V_{DS} \ll 2(V_{GS}-$

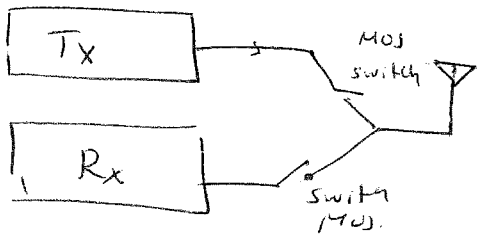
* MOS Devices acts as a switch



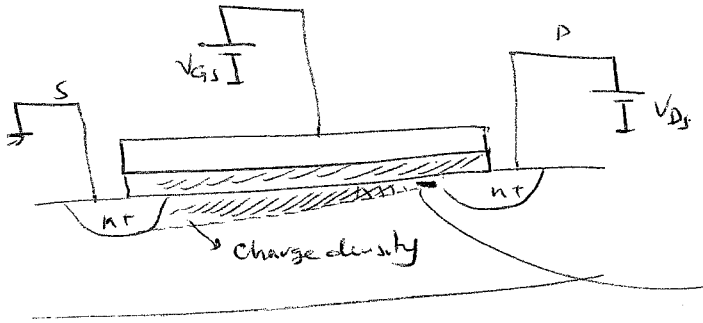
⇒ ON — $V_{GS} > V_{th}$

OFF — $V_{GS} \leq V_{th}$

Bluetooth System



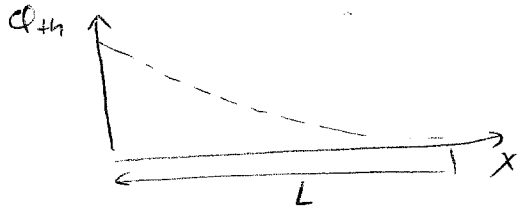
* I_D for $V_{DS} > V_{GS} - V_{th}$



$V_{GS} - V_{DS} = V_{th}$

$V_{GS} - V_{th} = V_{DS}$

Pinch off



Redrive The I/V equation

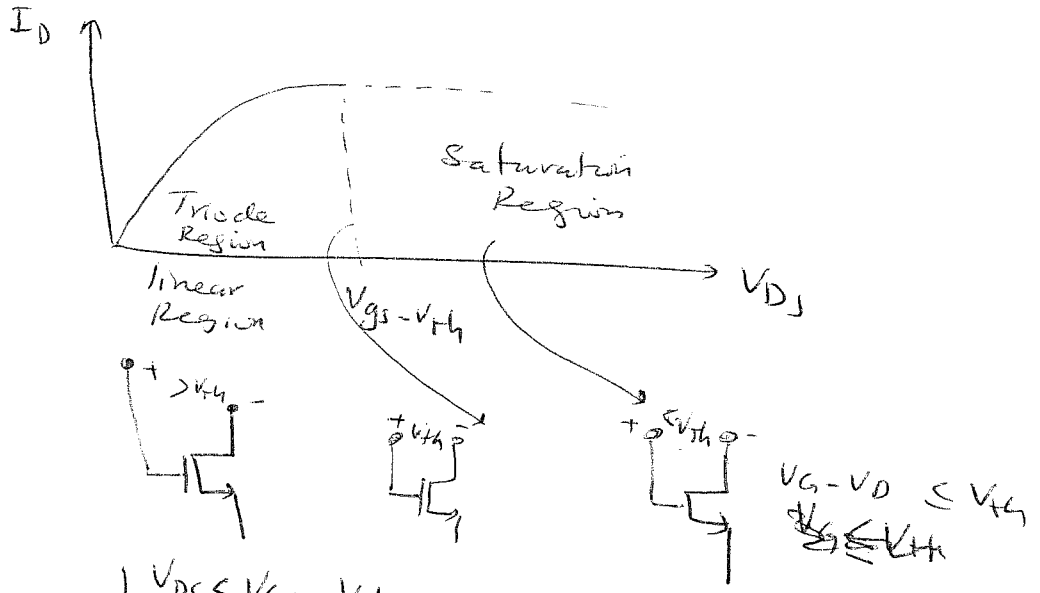
$$\int_0^L I_D \, dx = \int_0^{V_{gs}-V_{th}} \mu_n C_{ox} \frac{W}{L} (V_{gs} - V_{th} - V_{DS}) \, dV$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{gs} - V_{th})^2 \qquad V_{DS} \geq V_{gs} - V_{th}$$

Constant Current

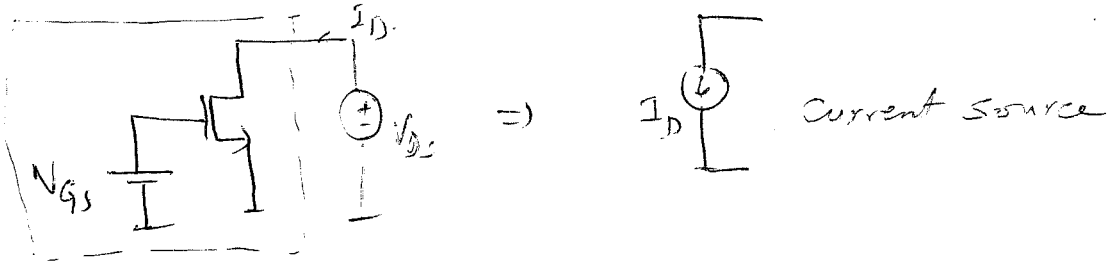
$$I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_{th})V_{DS} - \frac{1}{2}V_{DS}^2\right] \qquad V_{DS} \leq V_{GS} - V_{th}$$

$$= \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{th})^2 \qquad V_{DS} \geq V_{GS} - V_{th}$$



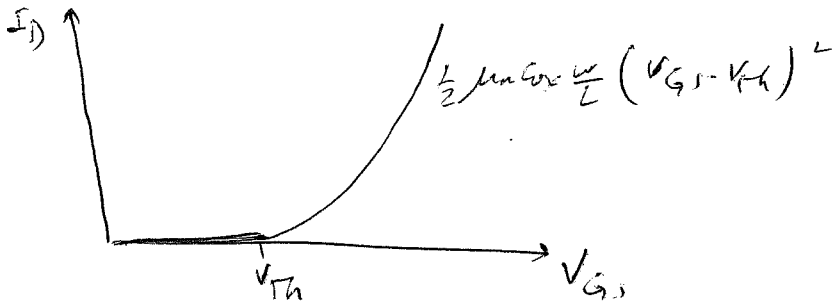
Triode Region $\begin{cases} V_{DS} \leq V_{GS} - V_{th} \\ V_G > V_D + V_{th} \end{cases}$

Observation:-

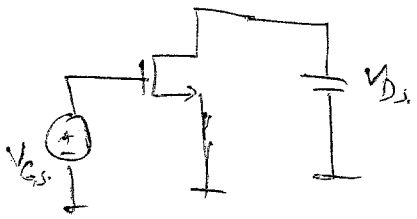


$(V_{DS} > V_{GS} - V_{th})$

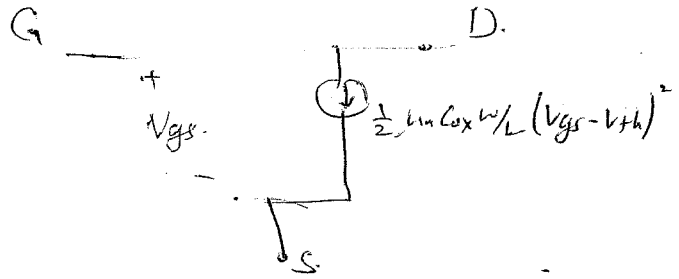
$I_G - V_{GS}$ Characteristic



Exercise: Prove that the MOS device always turns on if $V_{DS} > 0$



- Simple Model in Saturation



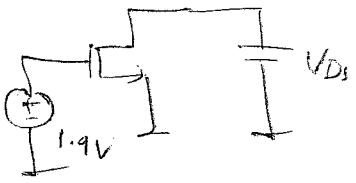
Example :

$\mu_n C_{ox} = 100\ \mu A/V^2$

$V_{th} = 0.5V$

$W/L = \frac{5\ \mu m}{0.5\ \mu m}$

Design 1 mA current source



$1mA = \frac{1}{2} \times 100\ \mu A/V^2 \times 10\ (V_{GS}-0.5)^2$

$V_{GS} = 1.9V$ ✱

for saturation if $V_{DS} > V_{GS} - V_{th}$

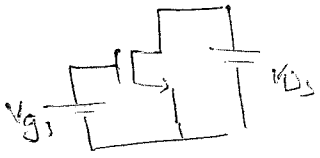
$> 1.9 - 0.5 = 1.4V$

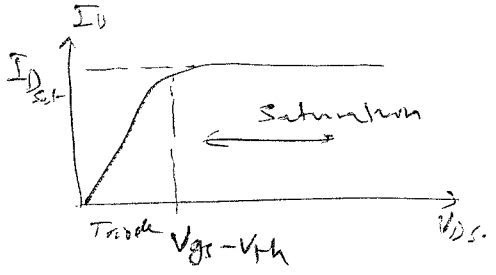
lect 12

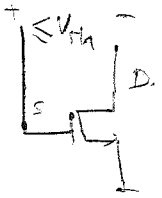
Today's lect:

- Channel length modulation
- Biasing

Review:

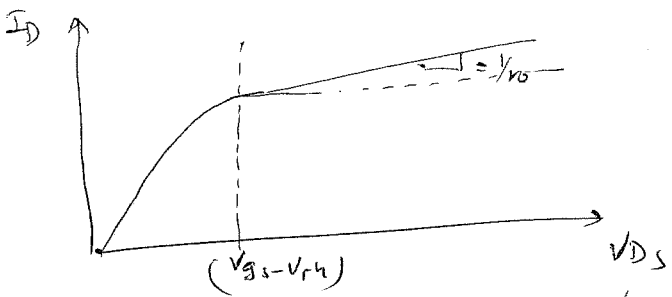


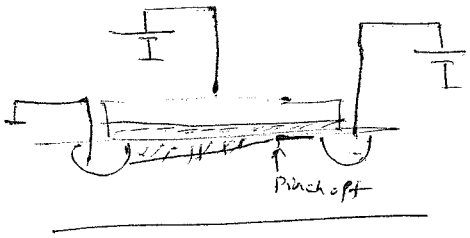




Sat: $I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS}-V_{th})^2$

* Channel length Modulation :-

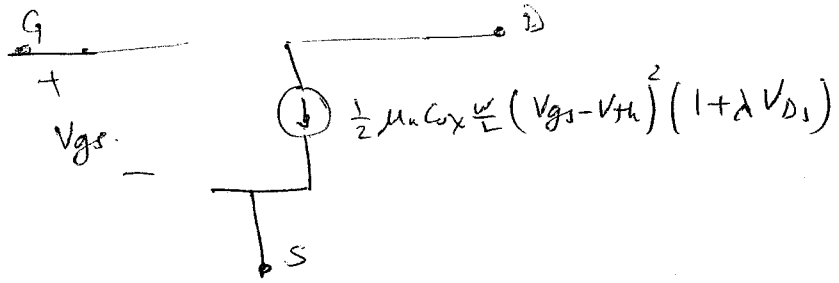




As V_{DS} increases, the channel lenght L ↓

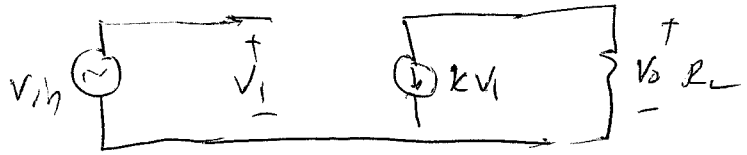
$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{th})^2(1+\lambda V_{DS})$$

$\lambda = \frac{1}{V}$: channel length modulation coefficient.



Biasing :

Lets build an amplifier



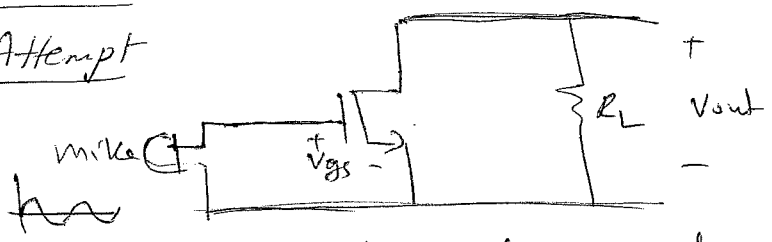
$V_o = -kR_L V_{in}$

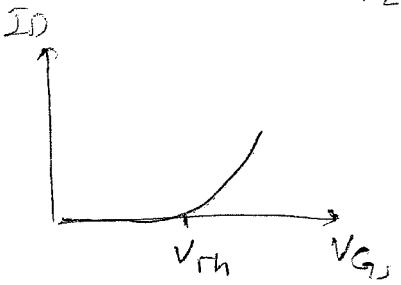
if $kR_L > 1$

⇒ amplification

Assume $\lambda = 0$

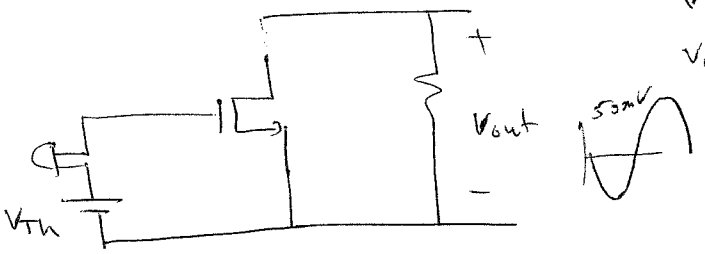
First Attempt





This # circuit not create current
⇒ isn't amplifier.

Second attempt



$V_{GS} = V_{TH}$

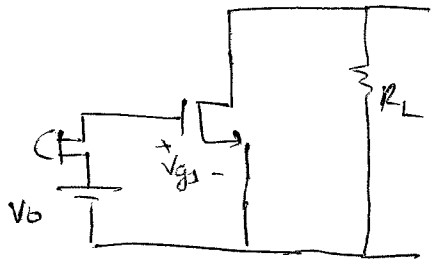
$V_{in} = V_G = V_{TH} + 5mV\sin\omega t$

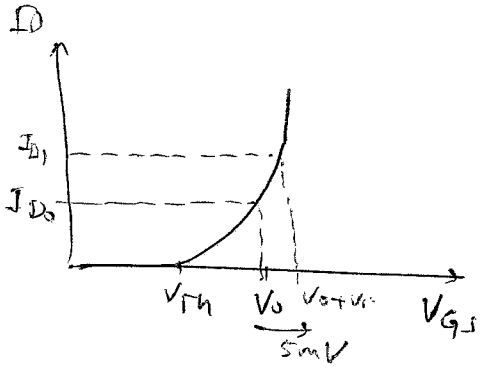
Example $\mu_n C_{ox} = 100\,\mu A/V^2$ $\quad W/L = 10$, $\quad V_T = 0.5V$

$I_D = \frac{1}{2} \times (100\,\mu A/V^2)(10)(5mV)^2 = 12.5\,nA$

$V_o = R_L I_D \Rightarrow R_L = \frac{50mV}{12.5nA} = 4M\Omega$ (Large resistance) not particular value.

Third attempt





$V_{GS} = V_o$

Example $V_o = 0.9V$

$V_{TH} = 0.5V$

$I_{D0} = \frac{1}{2}\mu_n C_{ox} W/L (V_{gs} - V_{th})^2 = 80\,\mu A$

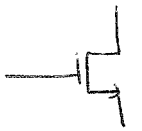
$I_{D1} = \frac{1}{2}\mu_n C_{ox} W/L (0.905) = 82\,\mu A$

Change of $I_D = 2\,\mu A \Rightarrow R_L = 25\,k\Omega$

⇒ Need to bias the transistor by (creating) applying proper current and therminal voltages (in the absence signals) so that the device can ampify the signal

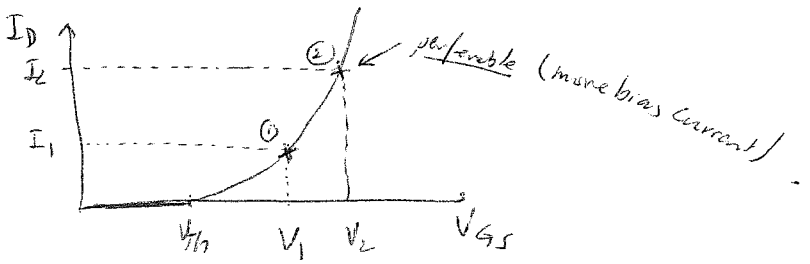
- Observations:-

① A MOS device convert a voltage to a current.
Voltage to current Converter

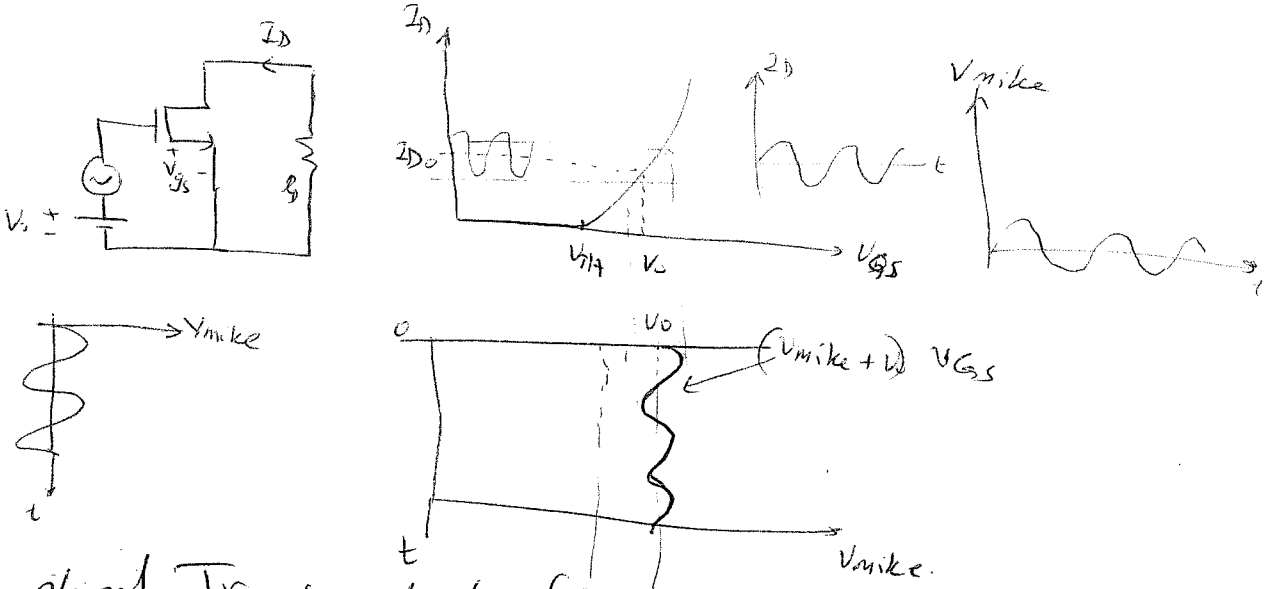


V/I Converter = called transconductor

② which operating point is preferred



Combining Time Response with I/V Characteristics



Concepts of Transconductance (g_m)

$$g_m = \frac{dI_D}{dV_{GS}}$$

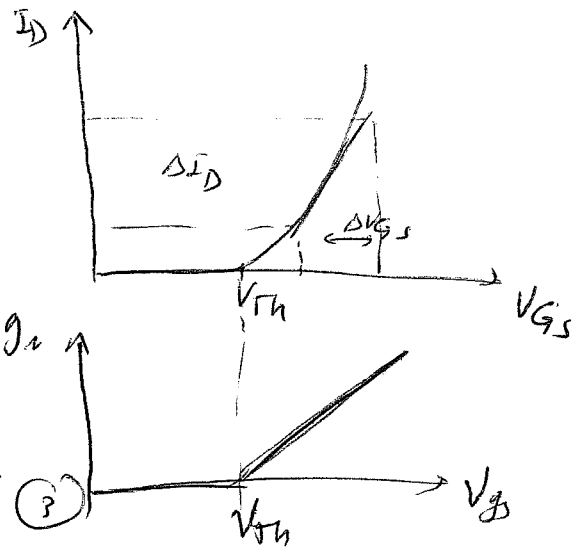
Unit $\frac{1}{\Omega}$ Siemens. (S)

$$g_m = \frac{d}{dV_{GS}}\left(\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{th})^2\right)$$

$$= \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{th}) \rightarrow (1)$$

$$g_m = \frac{2I_D}{V_{GS}-V_{th}} \rightarrow (2)$$

$$g_m = \sqrt{2I_D \mu_n C_{ox} W/L} \quad (3)$$



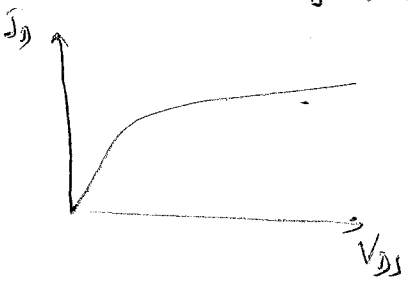
lect 33

Today's lect.

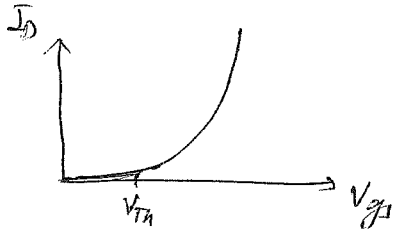
- More on Transconductance
- Large Signal and Small Signal operation.

Review:- Region of operation ← Triode / saturation

- Channel length modulation



$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})$$



- Transconductance $g_m = \frac{\partial I_D}{\partial V_{GS}}$

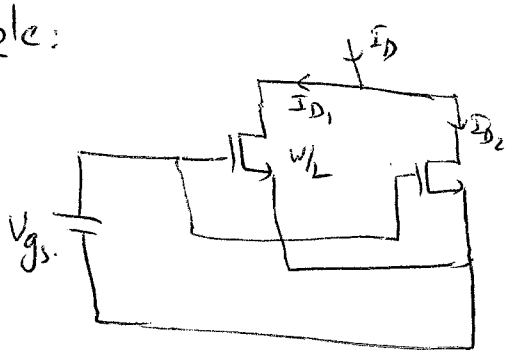
- g_m Expressions:

$$g_m = \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH}) \Longrightarrow \begin{cases} g_m \propto \frac{W}{L} & \text{when } (V_{GS}-V_{TH}) \text{ ct} \\ g_m \propto (V_{GS}-V_{TH}) & \text{if } (W/L) \text{ ct} \end{cases}$$

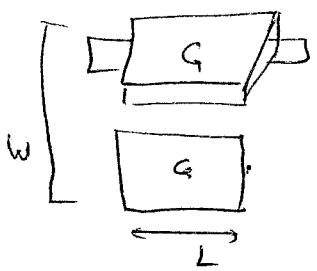
$$= \frac{2I_D}{V_{GS}-V_{TH}} \Longrightarrow g_m \propto \frac{1}{V_{OV}} \quad \text{if } I_D \text{ ct}$$

$$= \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D} \Longrightarrow (V_{GS}-V_{TH}) \text{ ct} \Rightarrow g_m \propto I_D$$

Example:



If V_{GS} = ct



$$I_{D1} = I_{D2} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2$$

$$I_{D1} + I_{D2} = 2\left(\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2\right)$$

$$= \frac{1}{2}\mu_n C_{ox}\,2\left(\frac{W}{L}\right)(V_{GS}-V_{TH})^2$$

The new composed device is twice W

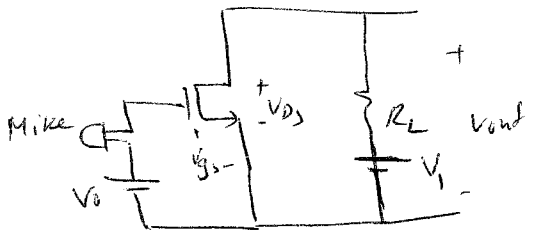
Old $g_m = \dfrac{2I_D}{V_{GS}-V_{TH}}$ for one transistor because V_{GS} is the same for the two transistors

new $g_{m_{new}} = 2\left(\dfrac{2I_D}{V_{GS}-V_{TH}}\right) = 2g_{m_{old}}$.

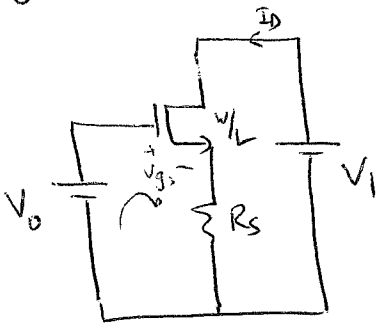
Let's build an amplifier

$V_{GS} = V_0$

$V_1 = R_L I_D + V_{DS}$



Large Signal Operation:



Find the current

KVL: $V_0 = V_{GS} + R_S I_D$

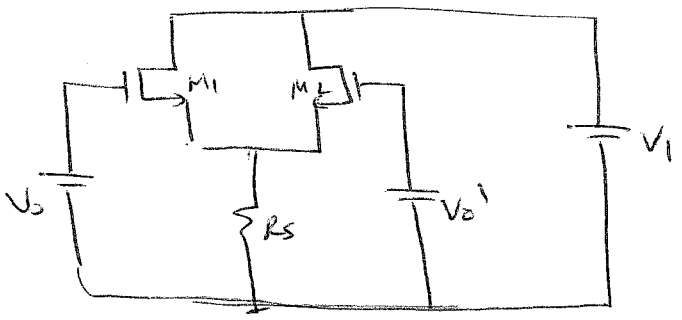
$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2$

$$V_{GS} = \sqrt{\frac{2I_D}{\mu_n C_{ox} W/L}} + V_{TH}$$

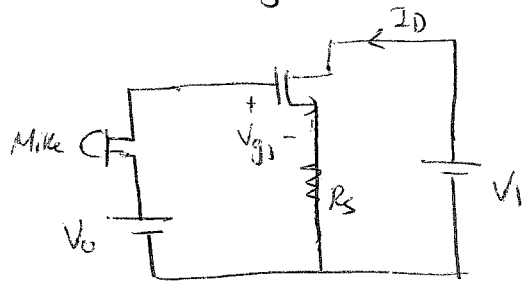
$$\Rightarrow V_0 = \sqrt{\frac{2I_D}{\mu_n C_{ox} W/L}} + V_{TH} + R_S I_D$$

Solving to find I_D

Example



Let's add a signal



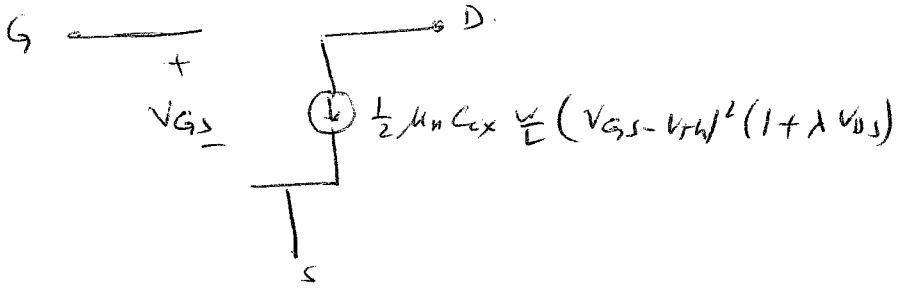
$V_{Mike} = V_m \sin\omega t$

$I_D R_S + V_{GS} = V_0 + V_m \sin\omega t$

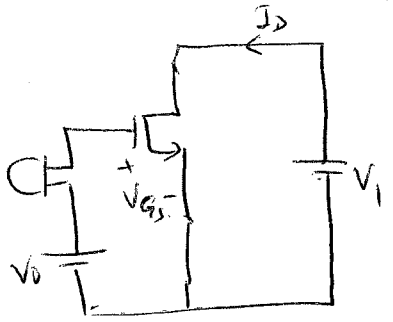
$$\sqrt{\frac{2 I_D}{\mu_n C_{ox} \frac{W}{L}}} + V_{TH} + I_D R_S = V_0 + V_m \sin\omega t$$

Large signal operation if V_m is not small.
that is not dc analysis

⇒ Use Large signal Model of Transistor



Small Signal operation:



$\lambda = 0$

$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2$

$V_{GS} = V_m \sin\omega t + V_0$

$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH} + V_m \sin\omega t)^2$

assume $V_m \ll V_{GS} - V_{TH}$

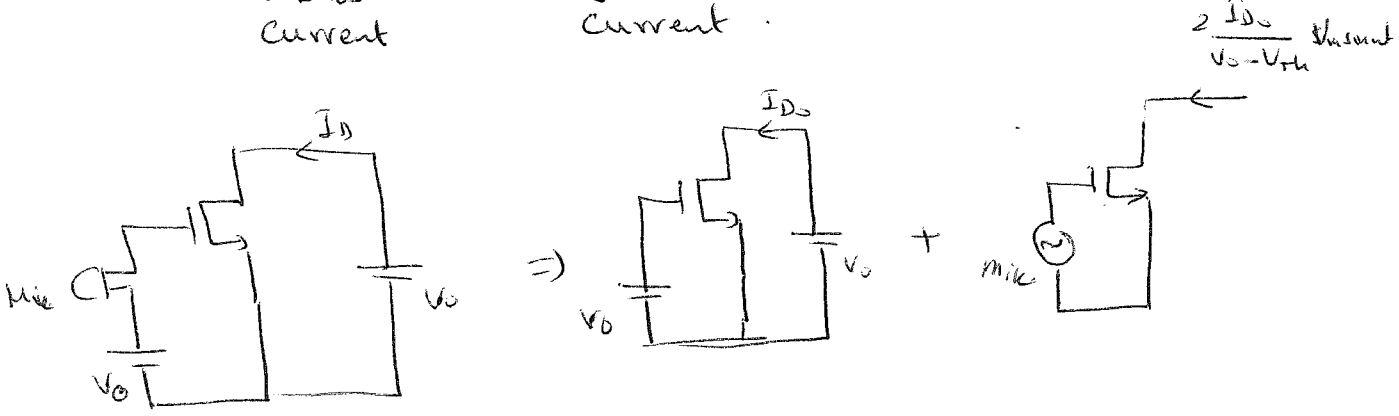
math $(1+\varepsilon)^2 = 1 + 2\varepsilon$

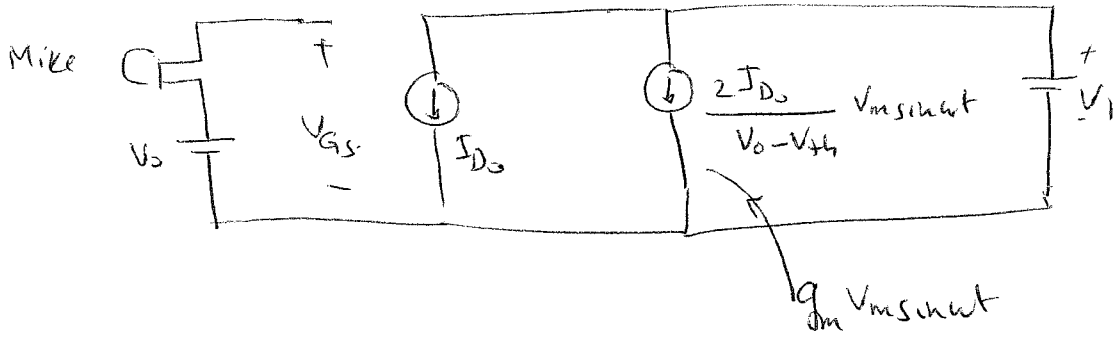
$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 \left(1 + 2 \cdot \frac{V_m \sin\omega t}{V_{GS} - V_{TH}}\right)$$

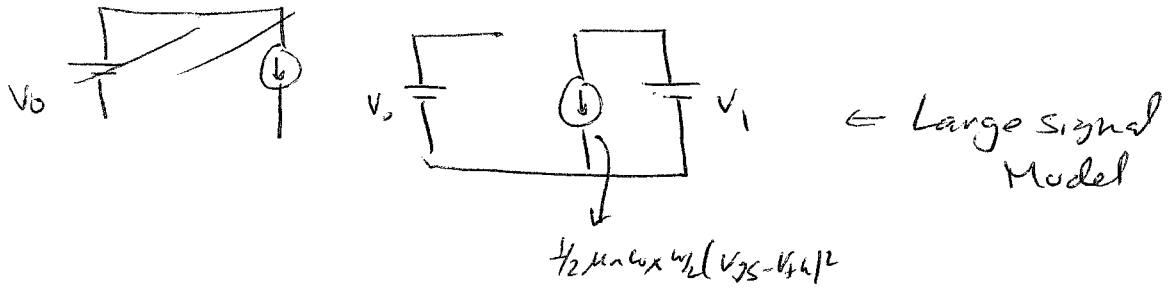
$= I_{D0}$

$$I_D = I_{D_0} + \underbrace{\frac{2I_{D_0}}{V_0 - V_{th}} V_m \sin\omega t}_{\text{signal current}}$$

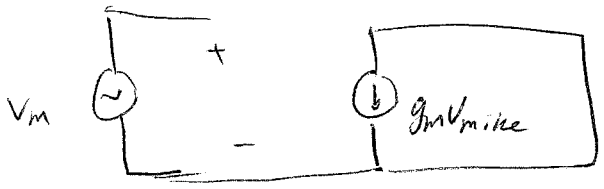
I_{D_0} ← the bias current







← Large signal Model

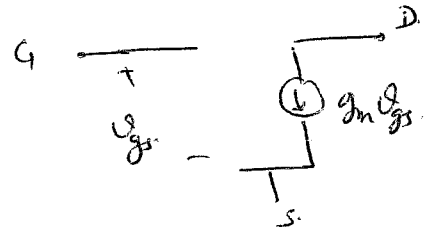


Small signal Model

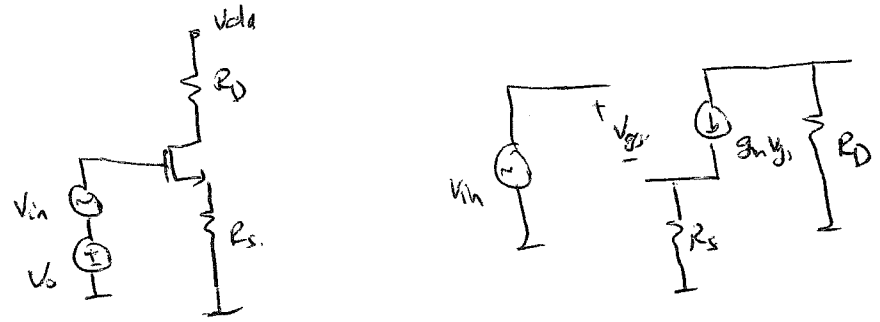
Today's lect.

- Move on large Signal and Small Signal Model
- Inclusion of channel length Modulation
- PMOS

Small Signal Model



Example Draw the small signal Model



Inclusion of channel Modulation

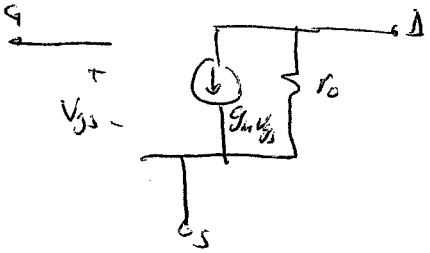
$$I_D = \tfrac{1}{2} \mu_n C_{ox} \tfrac{W}{L} (V_{GS} - V_{Th})^2 (1 + \lambda V_{DS})$$

$$\Delta I_D = \tfrac{1}{2} \mu_n C_{ox} \tfrac{W}{L} (V_{GS} - V_{Th})^2 (1 + \lambda \Delta V_{DS})$$

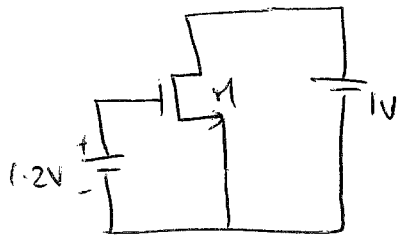
$$I_D + \Delta I_D = I_D + \tfrac{1}{2} \mu_n C_{ox} \tfrac{W}{L} (V_{GS} - V_{Th})^2 \lambda \Delta V_D$$

$$\frac{\Delta V_{DS}}{\Delta I_D} = \left[\tfrac{1}{2} \mu_n C_{ox} \tfrac{W}{L} (V_{GS} - V_{Th})^2 \lambda \right]^{-1}$$

$$\frac{\Delta V_{DS}}{\Delta I_D} = \frac{1}{\lambda I_D}$$



Ex:



$\mu_n C_{ox} = 100\,\mu A/V^2$

$V_{Th} = -0.5V$

$\lambda = 0.2\,V^{-1}$

Draw small signal Model

- Before going to finding the parameters we have to test if M is in saturation OR not.

Test $V_{GS} - V_{Th} \leq V_{DS} \Rightarrow$ Saturation

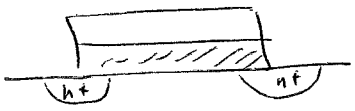
$0.7V \leq 1V$

$g_m = \mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{Th}) = 0.7\,mS = \frac{1}{1.43\,k\Omega}$

$r_o = \frac{1}{\lambda I_D}$, $I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{Th})^2 = 0.245\,mA$

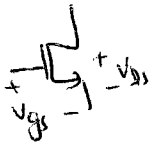
$r_o = 20.4\,k\Omega$

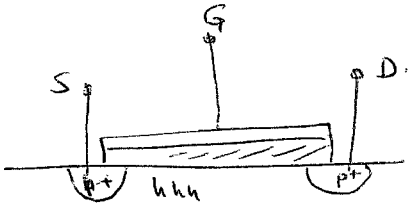
MOS Device Types:-



P-substrate

NMOS.

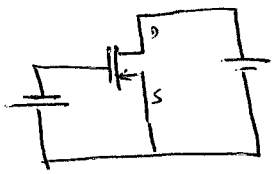


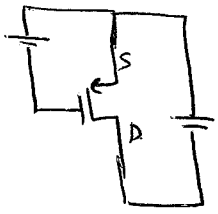


n-substrate

Hole of channel is created

- $V_G < V_S$
- Threshold is negative
- $V_D < V_S$

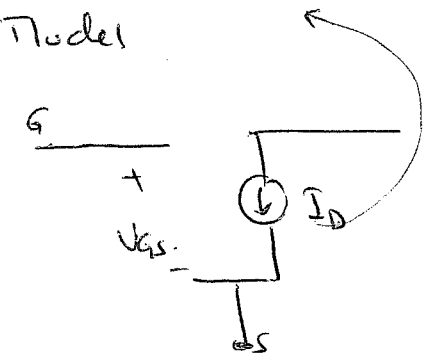


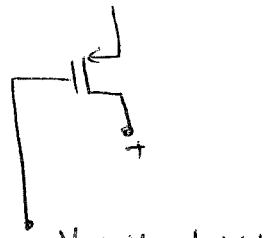


In Saturation

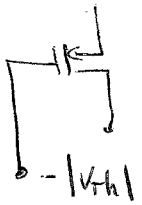
$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1-\lambda V_{DS}) \qquad \lambda > 0$$

Large signal Model

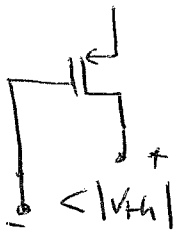




Triode

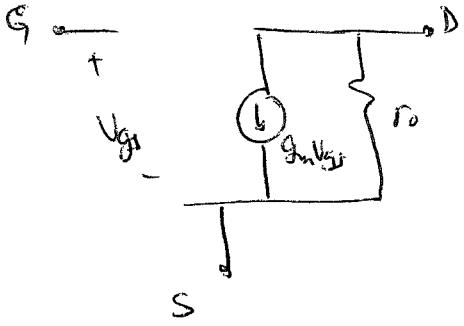


Edge



Saturation

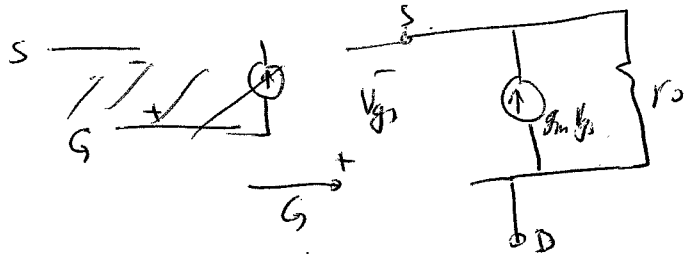
Small signal



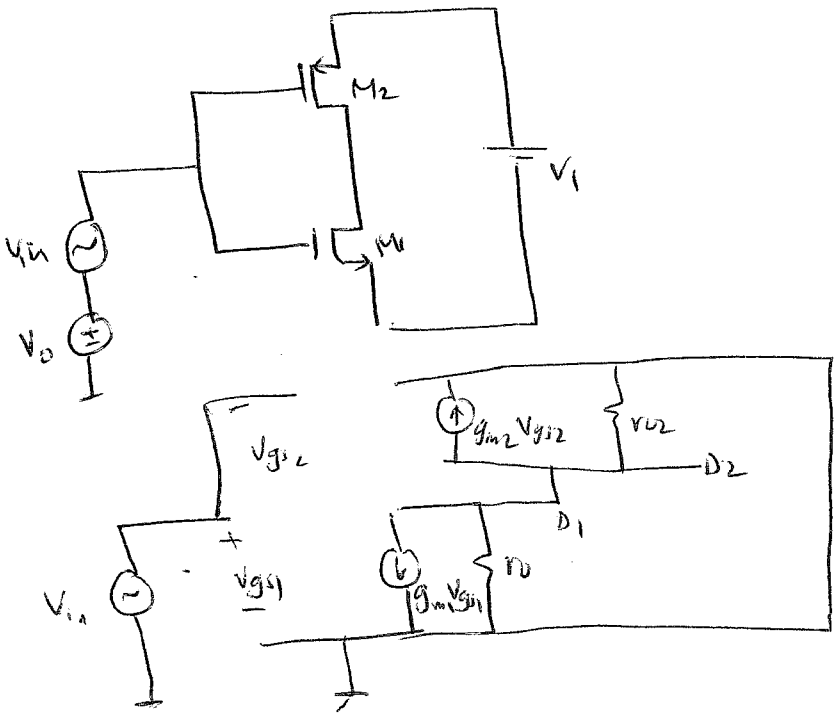
⇒ NMOS

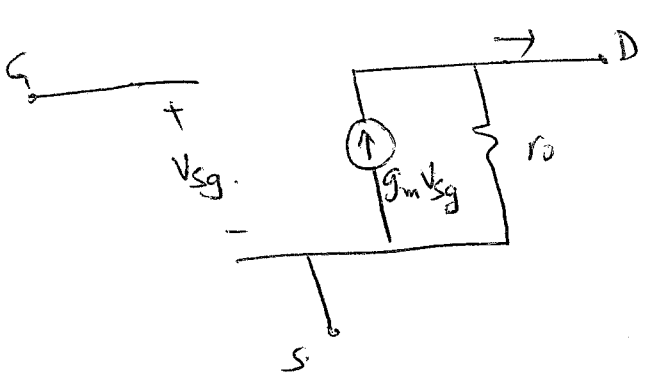
PMOS



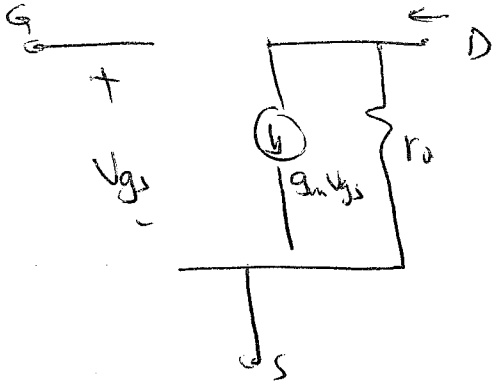


Example





PMOS



$$r_o = \frac{1}{\lambda I_D}$$

$$g_m = \frac{2I_D}{V_{OV}}$$

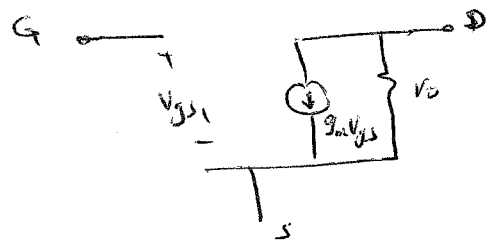
lect. 35
Chapter 7

Today's lect.

- CMOS Technology
- Introduction to CMOS Amplifier
- The Common Source amplifier

Review:

- MOS small signal Model



$$r_o = \frac{1}{\lambda I_D}$$

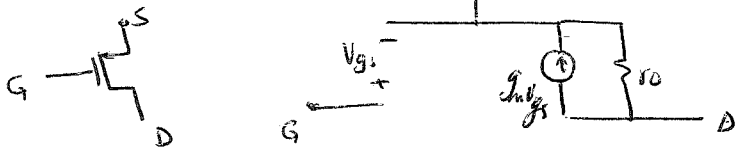
$$g_m = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})$$

$$= \frac{2 I_D}{V_{gs} - V_{TH}}$$

$$= \sqrt{2 \mu_n C_{ox} W/L \; I_D}$$

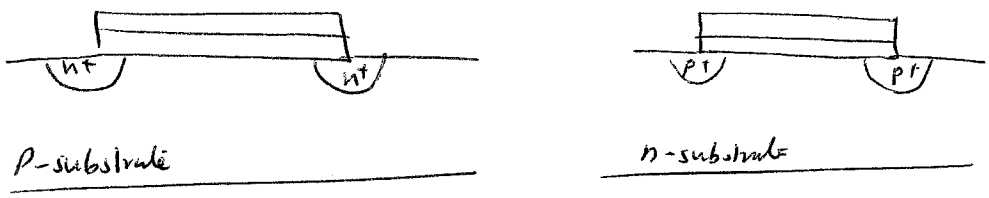
- Analysis steps : - Calculate bias conditions
  - Draw the small signal Model

- PMOS Device

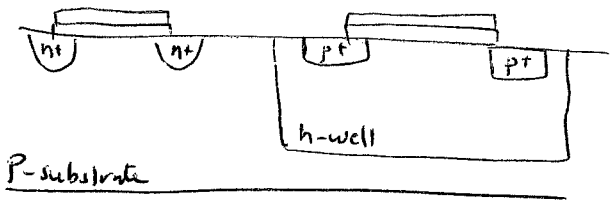


$V_S > V_D$.
V_g

- CMOS Technology: - Complementry MOS
  - We have both NMOS and PMOS in our circuit



CMOS



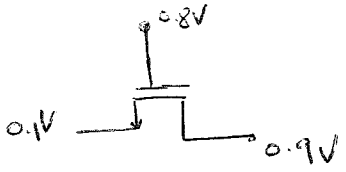
Example:-





Drain must be lower than gate by V_{th} To be at saturation

E



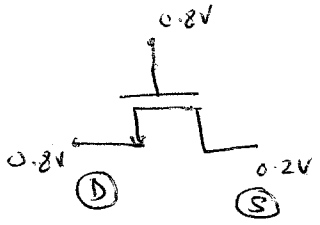
$V_{Th_N} = 0.5V$

$V_{GS} = V_g - V_s = 0.8 - 0.1 = 0.7V$ ⇒ Device is ON

$V_{GS} - V_{Th} = 0.7 - 0.5 = 0.2V$

$V_{DS} = V_D - V_S = 0.9 - 0.1 = 0.8V > (V_{GS} - V_{Th})$

⇒ Device in saturation



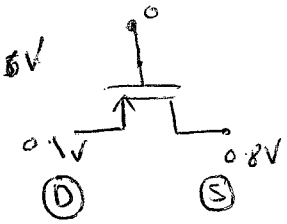
$V_{Th_N} = 0.5V$

Definition of source is the terminal that have voltage lower than drain.

$V_{GS} = 0.6V > V_{th}$ ⇒ Device is ON

$V_{DS} = 0.6V > (V_{GS} - V_{Th})$ ⇒ Device is saturation

$V_{Th_P} = -0.8V$



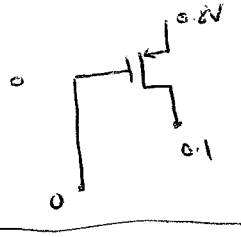
In PMOS the source have to be positive than Drain

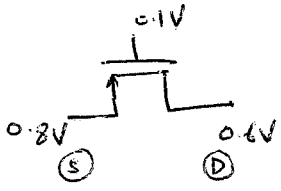
$V_{GS} = -0.8V$ ⇒ D is ON

$V_{GS} - |V_{Th}| = -0.2V$

$V_{DS} = -0.7V$

$V_{GS} - V_{Th} > V_{DS}$ ⇒ Saturation





$V_{GS} = -0.7V < V_{Th_P}$ ⇒ Device is ON

$V_{GS} - V_{Th_P} = -0.1V$

$V_{DS} = -0.2V$

$(V_{GS} - V_{Th_P}) > V_{DS}$ ⇒ Device is saturate.

CMOS Amplifier

Amplifier design procedure:-

1) Select an amplifier topology.
2) Bias the transistor to obtain the proper value for (g_m, r_o)
3) Determine the characteristics of the circuit

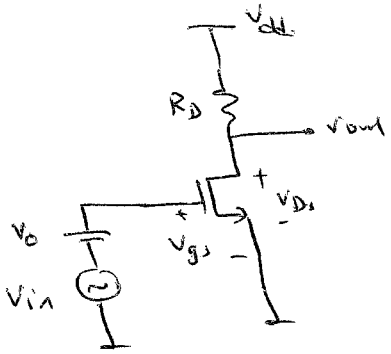
Amplifier Characteristics

1) Gain $A_v = \frac{v_o}{v_{in}}$ — Voltage gain



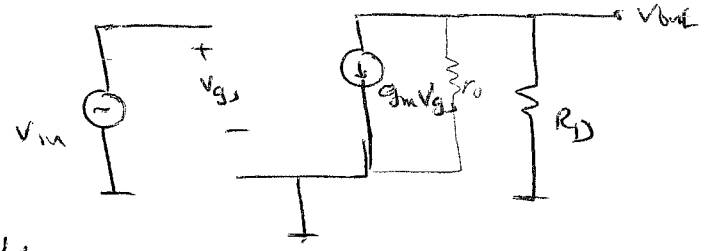
2) Power dissipation.
3) Input / output impedance.

Common Source Amplifier



Input is applied at the gate
Output is taken @ the Drain

For $r_o = \infty$ $\lambda = 0$



$v_{in} = v_{gs}$.

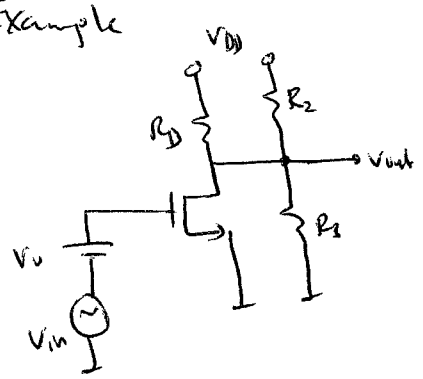
$v_{out} = -g_m v_{gs} R_D = -g_m R_D v_{in}$.

$$\boxed{A_v = -g_m R_D} = -g_m \left(\begin{array}{c} \text{Total resistance connected} \\ \text{between Drain and ac GND} \end{array} \right)$$

If we take the length modulation effect

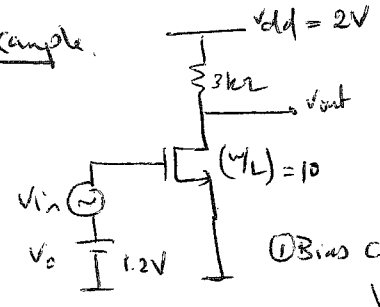
If $r_o \neq \infty$ ($\lambda \neq 0$) $\Rightarrow A_v = -g_m (R_D \| r_o)$

Example



$A_v = -g_m (R_D \| R_2 \| R_S)$

Example.



$\mu_n C_{ox} = 100 \mu A/V^2$

$V_{Th} = 0.5V$

$\lambda = 0$

find ① bias condition ② Av.

① Bias condition

$V_{GS} = 1.2V \quad V_S = 0.$

② Assume Saturation Region

$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{TH})^2 = 245 \mu A.$$

$$V_{DS} = V_{dd} - I_D R_D = 2 - 245\mu A \times 3k = 1.265V$$

Since $V_{DS} > (V_{GS} - V_{TH}) \Rightarrow$ M is in saturation.

③ Calculate the small signal parameters:

$$g_m = \frac{2I_D}{V_{GS} - V_{TH}} = 0.7 mS = \frac{1}{1.43 k\Omega}$$

4) The voltage gain $A_v = -g_m R_D$

$= -2.1$

Need to double the gain

①- Try doubling R_D.

if we double R_D, we have to check the bias condition and the transistor is still in saturation Region

doubling R_D that causes to Reducing V_{DS}.

- If I_D is still to 245 μA $\Rightarrow$ $V_{DS} = V_{DD} - R_D I_D = 0.53V$

$V_{DS} < (V_{GS} - V_{th}) \Rightarrow$ M isn't in saturation

0.53 0.7V $\Rightarrow$ M is in triode Region.

② Try increasing g_m:

$$g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D}$$

→ I_D increases

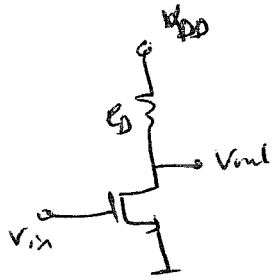
or

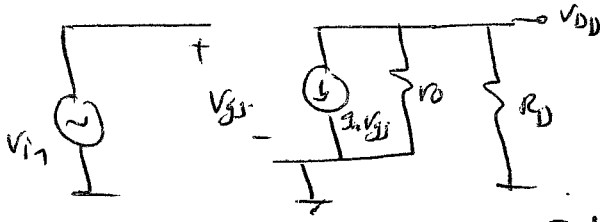
→ W/L increase.

- By increasing $I_D \Rightarrow V_{DS} \downarrow \rightarrow$ go to triode.
- By increasing $(W/L) \Rightarrow$ we can increase the W/L to sufficiently large

Subthreshold condition $\Rightarrow g_m \cong \frac{I_D}{1.5 V_T}$ $\quad V_T = \frac{kT}{q}$

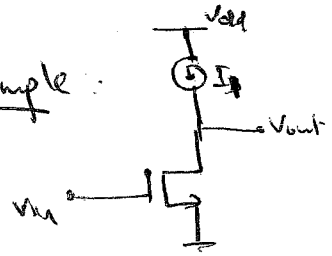
- Inclusion of Channel length modulation





$$A_V = -g_m (R_D \| r_O) \qquad r_O = \frac{|V_{DD}|}{\lambda I_D}$$

Example:

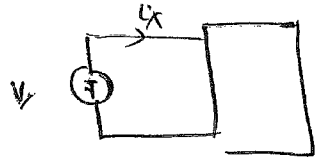


$$A_V = -g_m (\infty \| r_O)$$
$$= -g_m r_O$$

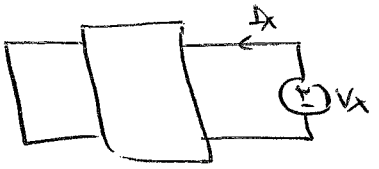
(Intrinsic gain) is the max gain we can obtain

$$g_m r_O \cong (5-10)$$

- Concept of Port Impedance



$$R_{in} = \frac{V_X}{i_X}$$



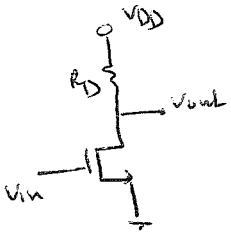
$$R_{out} = \frac{V_X}{i_X}\Big|_{V_{in}=0}$$

Today's lect.

- MOS current source
- Other variants of CS stage

Review

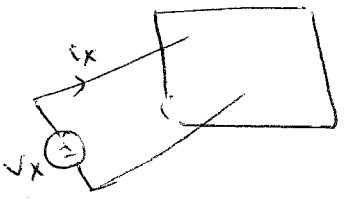
- CS stage



$A_v = -g_m R_D \qquad \lambda = 0$

$A_v = -g_m (R_D \| r_o) \qquad \lambda \neq 0$

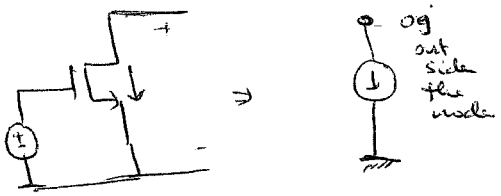
- Port Impedance:

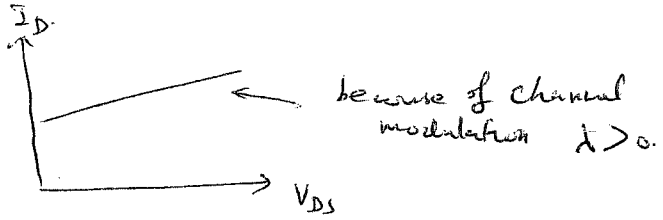


$R_{port} = \frac{V_x}{i_x}$

- Current Source:

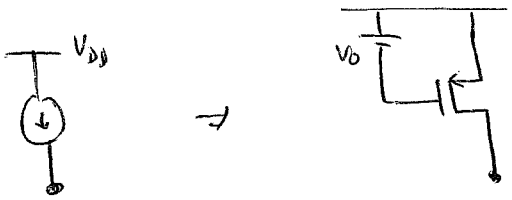
NMOS

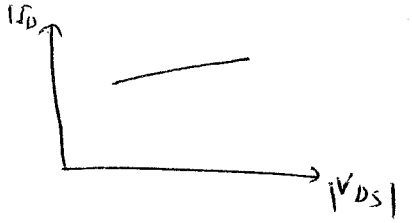




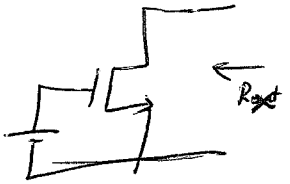
How to build current source the flow in to the node.

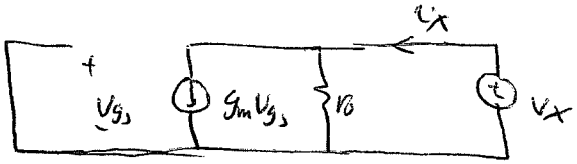
PMOS



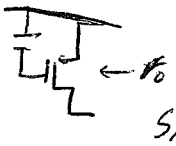


The equivalent small signal Circuit:





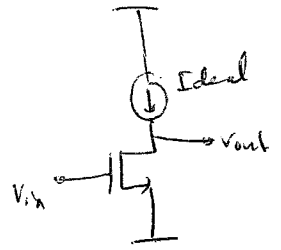
$V_{gs} = 0$ / $g_m V_{gs}$ is open circuit.



$R_x = \frac{V_x}{i_x} = r_o$

Small signal model of current source is r_o.

Common Source Stage with current source load.

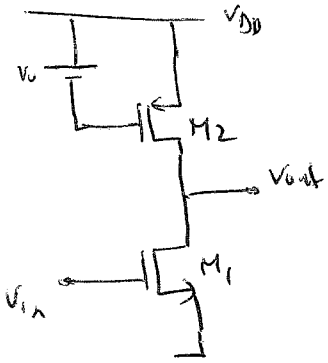


$A_v = -g_m(R_D \| r_o)$ $\quad R_D = \infty$

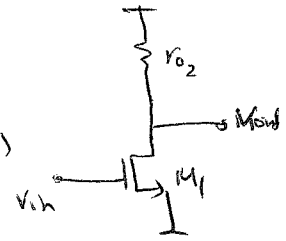
$\Rightarrow A_v = -g_m r_o$

we see that R_D reduces the gain.

Since we can see that the current go into the node
So the current source can be realized by PMOS



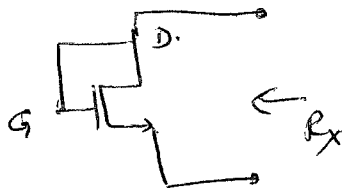
$\Rightarrow$

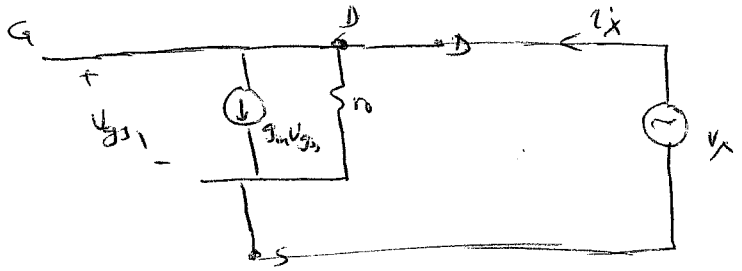


$A_v = -g_{m_1}(R_{Load})$
$= -g_{m_1}(r_{o1} \| r_{o2})$

both M_1, M_2 are in saturation

Diode Connected Device





$V_{gs} = V_x$

KCL @ D:

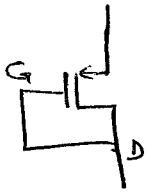
$$i_x = \frac{V_x}{r_o} + g_m V_x$$

$$= V_x\left[\frac{1}{r_o} + g_m\right]$$

$$R_x = \frac{V_x}{i_x} = \frac{1}{\frac{1}{r_o} + g_m} = \left(1/g_m \| r_o\right)$$

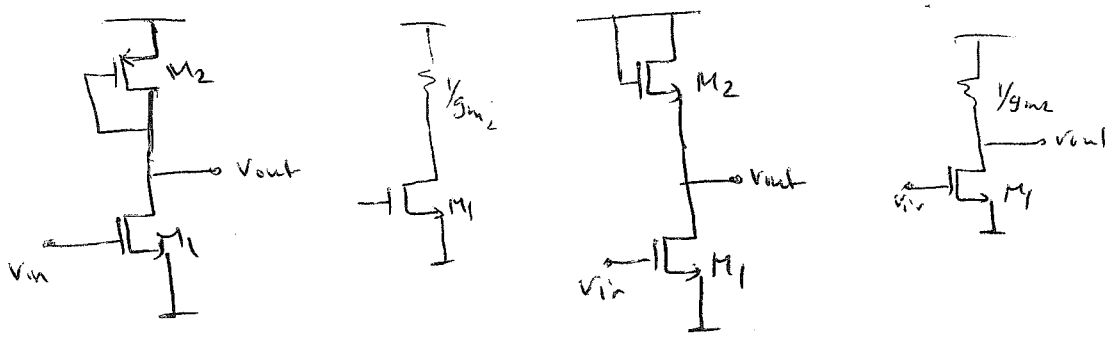
if we neglected the channel modulation $\lambda \doteq 0$

$$R_x = \frac{1}{g_m}$$



We can build the diode connected using PMOS

Common Source with Diode Connected load



PMOS diode connected load

FOR NMOS diode connected load :

For $\lambda = 0$ ⇒ diode connected is replace by $1/g_m$

$$A_v = -g_{m1}\left(\frac{1}{g_{m2}} \,//\, r_{o1}\right) \qquad r_{o1} = \infty$$

$$A_v = -\frac{g_{m1}}{g_{m2}}$$

$$g_m = \sqrt{2\mu C_{ox} \frac{W}{L} I_D}$$

$$g_{m1} = \sqrt{2\mu_n C_{ox} (W/L)_1 I_{D1}}$$

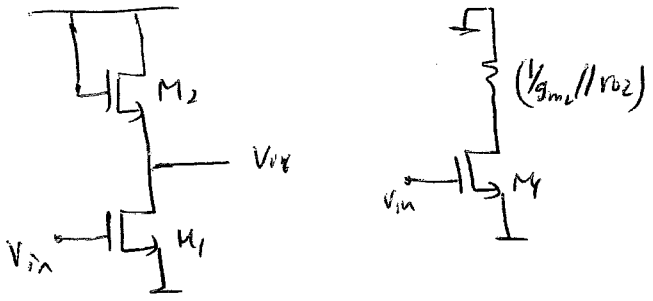
$$g_{m2} = \sqrt{2\mu_n C_{ox} (W/L)_2 I_{D2}} \qquad I_{D1} = I_{D2}.$$

$$A_v = \frac{g_{m1}}{g_{m2}} = -\sqrt{\frac{(W/L)_1}{(W/L)_2}}$$

⇒ the gain becomes depends only on the dimension of size.

⇒ gain becomes more stable.

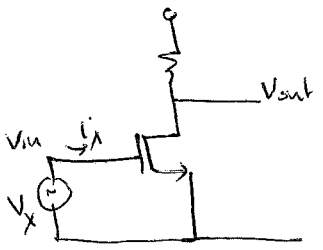
For $\lambda \neq 0$

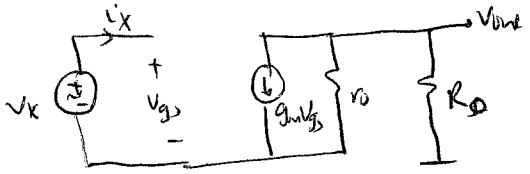


$$A_v = -g_{m1}\left(\frac{1}{g_{m2}} \,//\, r_{o2} \,//\, r_{o1}\right)$$

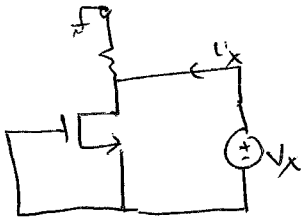
Input and Output Impedances

$$R_{in} = \frac{V_x}{i_x}$$

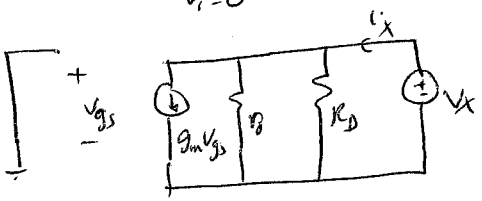




$R_{in} = \frac{V_x}{i_x} = \infty$ at low frequency



$$R_{out} = \left.\frac{V_x}{i_x}\right|_{V_i = 0}$$

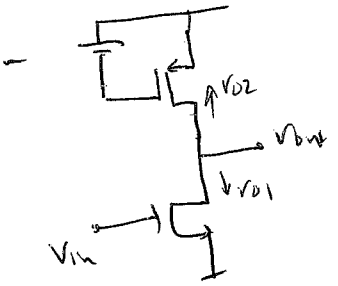


$V_{gs} = 0$

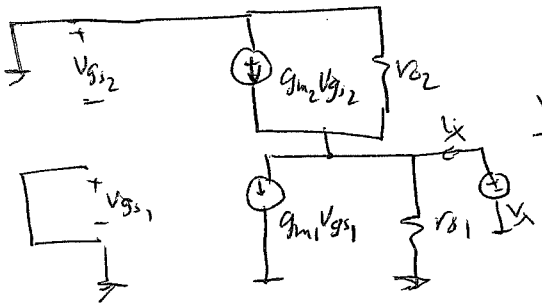
$g_m V_{gs} = 0 \Rightarrow$ open

$\Rightarrow \frac{V_x}{i_x} = R_D \| r_O$

Calculate R_{in} / R_{out}

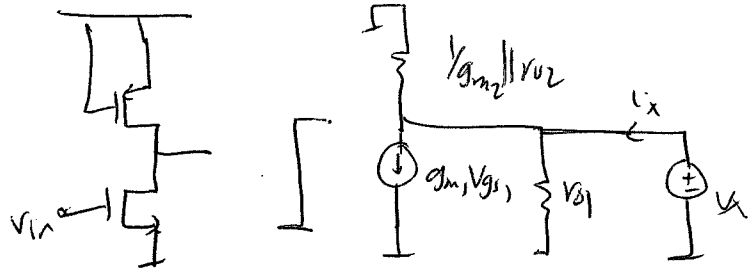


Calculate R_{out}



$\frac{V_x}{i_x} = r_{O1} \| r_{O2}$

Diode Connected load



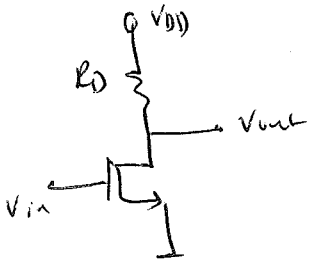
$$R_{out} = \frac{V_x}{i_x} = r_{O1} \| \frac{1}{g_{m2}} \| r_{O2}$$

$$\cong \frac{1}{g_{m2}}$$

Since general formulation

$A_v = -g_m R_D$ This value of A_v is not fixed

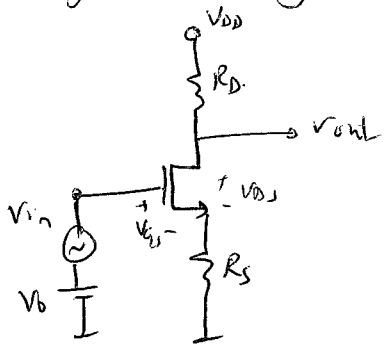
– Problem of Gain Variation



$$A_v = -g_m R_D$$
$$= -\sqrt{2\mu_n C_{ox} \frac{W}{L} I_D} * R_D$$

Factors affecting the gain :-
- Temperature (mobility is dep on temp)
- Supply voltage (I_D depends on supply voltage)
- Process variation.
- Signal level

CS Stage with Degeneration ($\lambda = 0$)



-Step (1) Bias Condition

$$V_b = V_{GS} + I_D R_S \quad \rightarrow (1)$$

Assume M in saturation

$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 \quad \rightarrow (2)$$

Solving (1, 2) gives V_{GS} and I_D

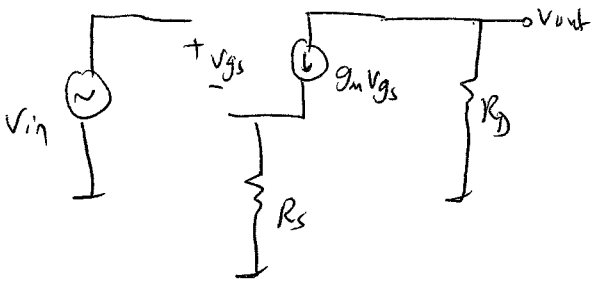
- Test the saturation Conditions

$$V_{DS} > (V_{GS} - V_{TH})$$

$$V_D = V_{DD} - I_D R_D$$

For Saturation $(V_{DD} - I_D R_D \geq V_G - V_{TH})$

Step (2): Analysis the ac parameters (A_v, R_{in}, R_{out})

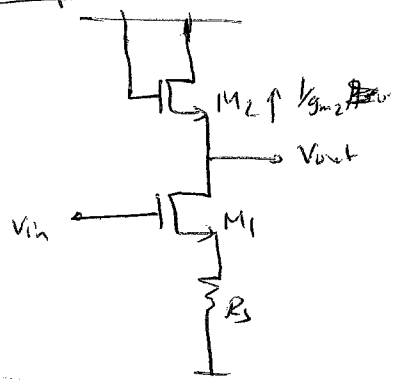


$$V_{out} = -g_m V_{gs} R_D$$
$$V_{in} = V_{gs} + g_m V_{gs} R_S$$
$$V_{in} = V_{gs}(1 + g_m R_S)$$
$$V_{gs} = \frac{V_i}{1 + g_m R_S}$$
$$V_{out} = -g_m \frac{V_i}{1 + g_m R_S} R_D$$
$$A_v = \frac{V_{out}}{V_{in}} = -\frac{g_m R_D}{1 + g_m R_S} = \frac{-R_D}{\frac{1}{g_m} + R_S}$$

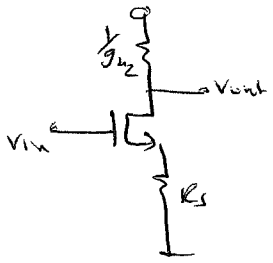
For $\lambda = 0$

$$A_v = -\frac{\text{Resistance tied between Drain and ac GND}}{1/g_m + \text{resistance tied between source and ac gnd.}}$$

Example:



$\lambda = 0$ Find A_v:



$$A_v = \frac{-1/g_{m2}}{1/g_{m1} + R_s}$$

- If $1/g_m \ll R_s \Rightarrow A_v \cong -\frac{R_D}{R_s}$ ⇒ the gain becomes less ~~not~~ depends on the temp. and the other parameters
- The gain becomes less but more stable
- Why is the gain less with Degeration:-



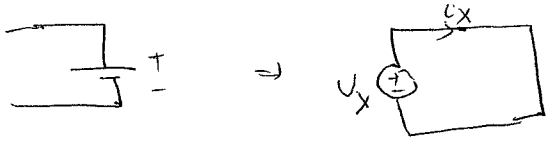
$A_v = -g_m R_D$ > $A_v = -\frac{R_D}{1/g_m + R_s}$

42:29

~~Independance~~ Impedance of Ideal V voltage and current source

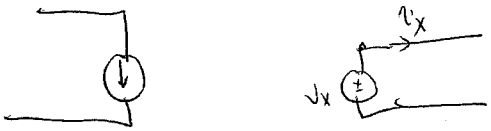
Constant

(*)



$R_{eq} = 0$

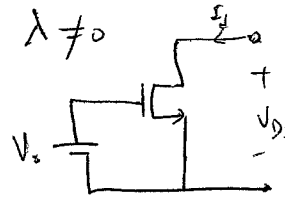
(*)

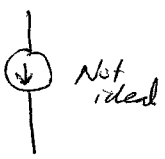


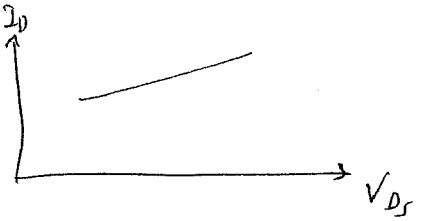
$R_{eq} = \infty$

Let's build current-source:

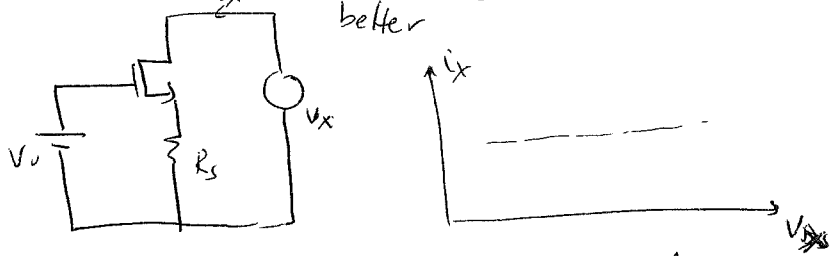
$\lambda \neq 0$





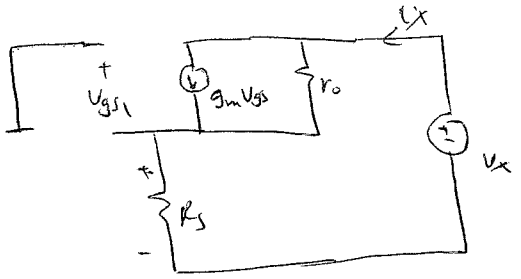


If we as R_S so the current becomes better



Calculate Rout and Compare it with ideal current

Small Signal Model



$$V_{gs_1} = -V_S = -i_X R_S$$

$$V_X = r_o\left[i_X - g_m V_{gs}\right] + R_S i_X$$

$$= r_o\left[i_X + g_m i_X R_S\right] + R_S i_X$$

$$= i_X\left[r_o + r_o g_m R_S + R_S\right]$$

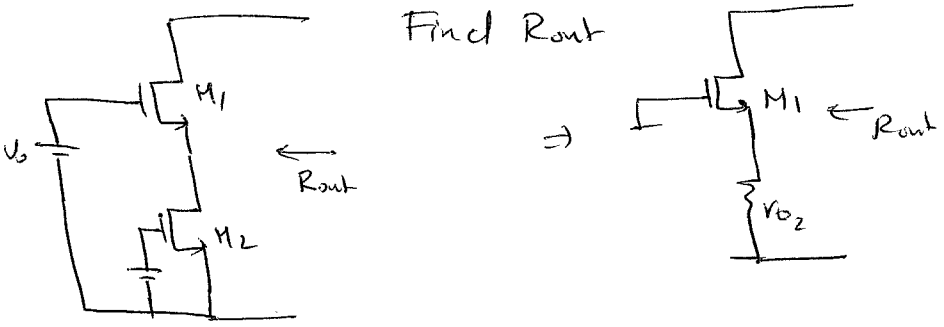
$$R_X = \frac{V_X}{i_X} = r_o + r_o g_m R_S + R_S$$

$$= r_o + R_S\left(1 + g_m r_o\right)$$

$\Rightarrow$ the impedance becomes greater than before so the current source becomes better.

Example:

Find Rout



$$R_{out} = r_{o1} + r_{o2}\left(1 + g_{m_1} r_{o1}\right)$$

lect 39

Today's lect.

- I/O Impedance of CS stage.
- Biasing techniques
- Common Gate Topology.



$\leftarrow R_{out} = r_o + (1 + g_m r_o) R_s$

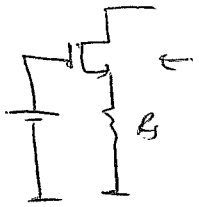
Review:

CS stage with degeneration



$$A_v = -\frac{R_D}{1/g_m + R_s}$$

- Current Source with degeneration

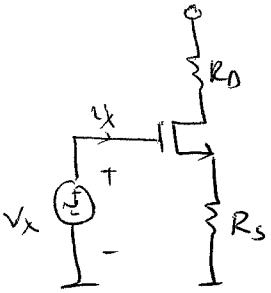


$\leftarrow$

$$R_{eq} = r_o + (1 + g_m r_o) R_s$$

* I/O Impedance of degeneration CS stage.

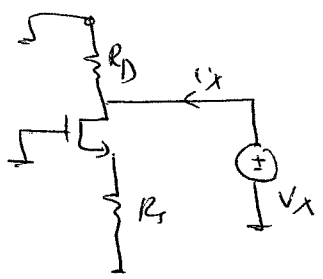
- Input Impedance:



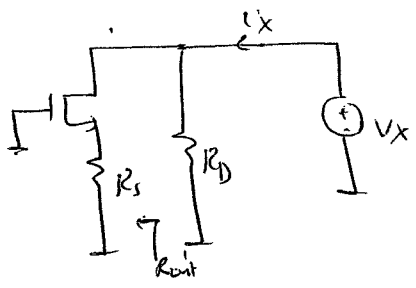
$i_x = i_G = 0$

$R_{in} = \infty$ at low frequency.

- Output Impedance: ($\lambda > 0$)

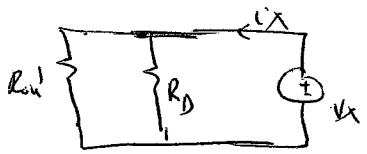


$\Rightarrow$

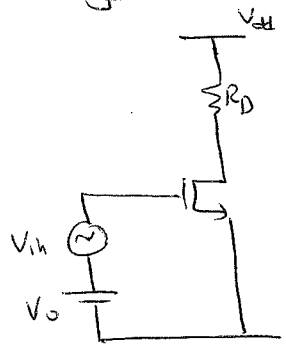


$$R_X = R_{out}' \,//\, R_D$$

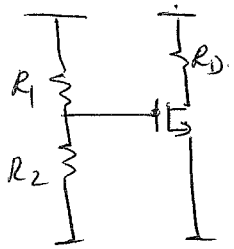
$$= \left[r_o + (1 + g_m r_o) R_s\right] // R_D$$



Biasing Techniques of CS :-



Here we have 2 batteries
so it is better to have only one battery.
V_o can be generate by resistive divider

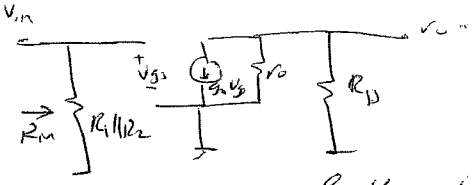


$$V_o = V_{R_2} = \frac{R_2}{R_1+R_2} V_{DD}.$$

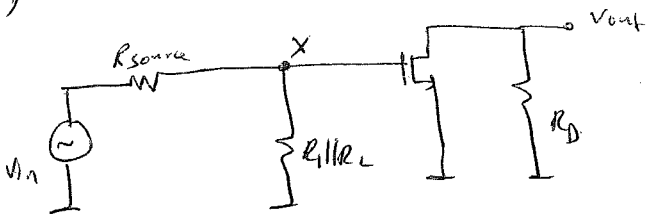
Observations

① Find R_{in}

$R_{in} = R_1 \| R_2$



② If we have internal resistance of the input source



Find $\frac{V_{out}}{V_{in}}$ for $\lambda = 0$

$$V_X = \frac{R_1 \| R_2}{R_1 \| R_2 + R_{source}} V_{in}.$$

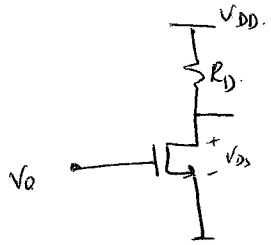
$$V_{out} = -g_m R_D V_X$$

$$= -g_m R_D \left[\frac{R_1 \| R_2}{R_1 \| R_2 + R_{source}}\right] V_{in}.$$

$$A_v = -g_m \left(\frac{R_1 \| R_2}{R_1 \| R_2 + R_{source}}\right) R_D.$$

Choose $R_1 \| R_2 \gg R_{source}$ to minimize the attenuation.

③ Can we increase R_D to increase the gain.



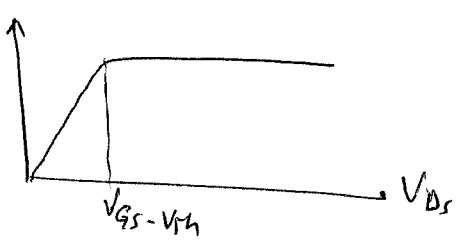
~~Increases~~

$$V_{DS} = V_{DD} - I_D R_D$$

- Increasing $R_D \Rightarrow V_{DS} \rightarrow$ reduces $\Rightarrow$ the MOS becomes closer to triode.

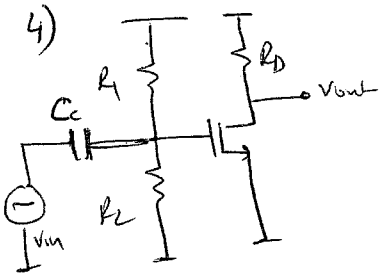
$$V_{DD} - I_D R_D \geq V_{GS} - V_{TH}$$

$$R_D \leq \frac{V_{DD} - V_{GS} + V_{TH}}{I_D}$$



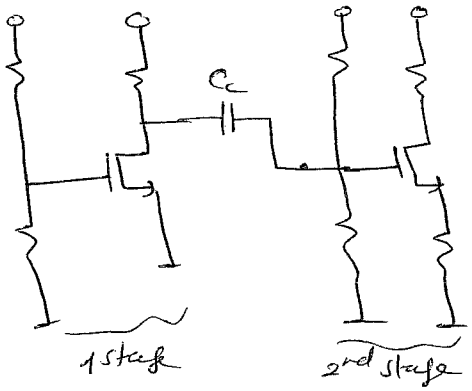
we can increase the gain that limits by $(V_{GS} - V_{DS}) = V_{DS}$

4)



- Here we have to add Coupling Capacitor to seperate the biasing condition.

(5) To Connect to amplifier (Cascading amplifier.)



(6) In saturation $I_D = \frac{1}{2}\mu C_{ox}\frac{W}{L}\left[V_{GS} - V_{TH}\right]^2$

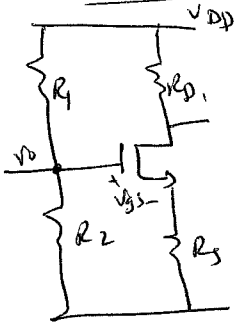
where $V_{GS} = V_G - V_S = V_{DD}\frac{R_2}{R_1+R_2}$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left[V_{DD}\frac{R_2}{R_1+R_2} - V_{TH}\right]^2$$

Sensitive to 1) Supply Voltage V_{DD}
2) process ($\mu_n C_{ox}$, V_{TH}, Temp)

⇒ The circuit becomes not stable.

(7) Sensitivity For CS stage with Degeneration



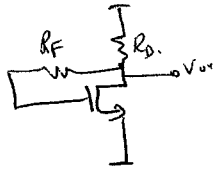
If $V_{DD}\uparrow \Rightarrow V_o \uparrow \Rightarrow V_{GS}$ is less sensitive to V_{DD}

$$V_o = \frac{R_2}{R_1+R_2}V_{DD} = V_{gs} + R_S I_D \longrightarrow (1)$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{GS}-V_{TH}\right)^2 \longrightarrow (2)$$

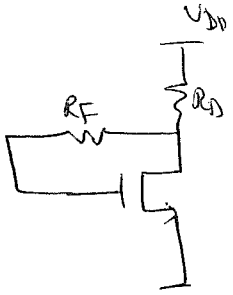
Solving (1, 2) gives I_D, V_{DS}, V_{GS}

(8) Self bias CS stage:



If $V_{TH}\downarrow \Rightarrow I_D \uparrow \Rightarrow V_{DS}\downarrow$, $V_D = V_G \Rightarrow V_G\downarrow$

⇒ self correction (less sensitivity to Variation).



$$V_D = V_{DD} - I_D R_D = V_G$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left[V_{GS} - V_{TH}\right]^2$$

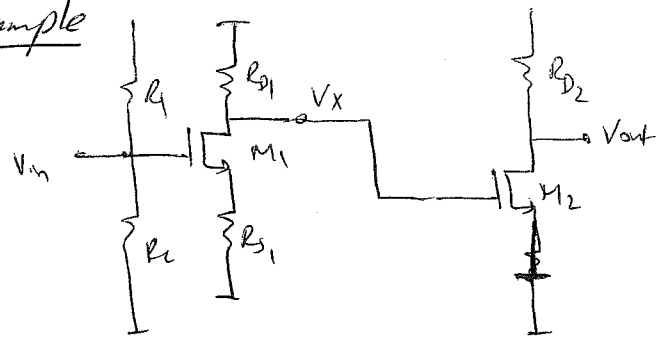
$$= \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left[(V_{DD} - I_D R_D) - V_{TH}\right]^2$$

Solving to find I_D.

Here is the circuit is generate to be @ saturation all the time. since $V_D = V_G$ ⇒ the drain can't be go down of V_G.
⇒ M is all time @ saturation

Cascading Stages

- Example

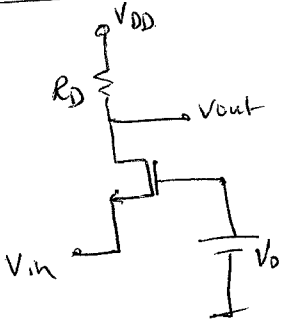


- How to Connect the two stages.
- By direct connect if V_{D1} satisfies the Baising Condition of M_2

Find $\frac{V_{out}}{V_{in}} = \frac{V_x}{V_{in}} * \frac{V_{out}}{V_{ix}}$

$$= -\left(\frac{R_{D1}}{\frac{1}{g_{m1}} + R_{S1}}\right) * \left(-g_{m2} R_{D2}\right)$$

Common Gate Topology



- Input is applied to source
- output is taken @ the Drain

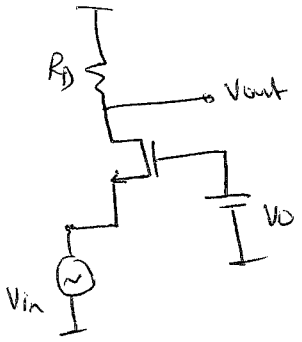
Step(1) : Bias Calculation

Step(2) : Small signal Analysis (Av, Rin, Rout)

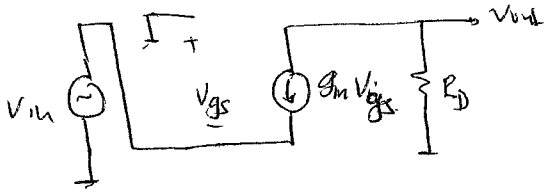
lecture

Today's lect.
- Common Gate Topology.
- Small Signal Analysis
- Bias design.

- Small Signal Analysis (A_v, R_{in}, R_{out})



$\lambda = 0$



$V_{gs} = -v_{in}$

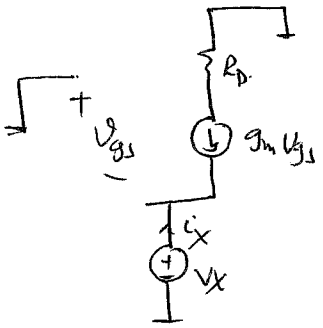
$v_o = +g_m V_{gs} R_D$

$= +g_m v_{in} R_D$

$$\boxed{A_v = \frac{v_o}{v_{in}} = +g_m R_D}$$

Input Resistance (Impedance)

$R_{in} = \frac{V_{in}}{i_{in}}$



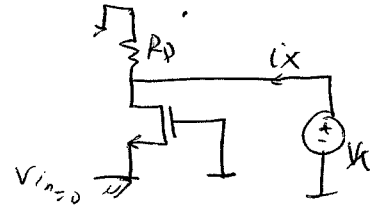
$V_{gs} = -V_x$

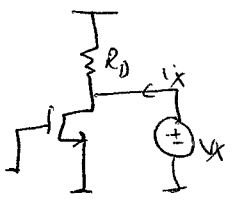
$i_x = -g_m V_{gs}$

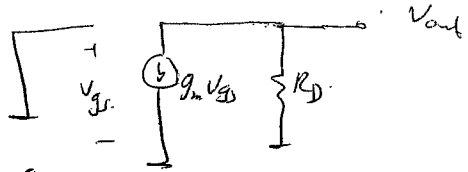
$i_x = g_m V_x$

$\Rightarrow \boxed{\frac{V_x}{i_x} = \frac{1}{g_m}}$ Small Value

$R_{out} = \frac{V_{out}}{i_{out}}\Big|_{V_{in}=0}$



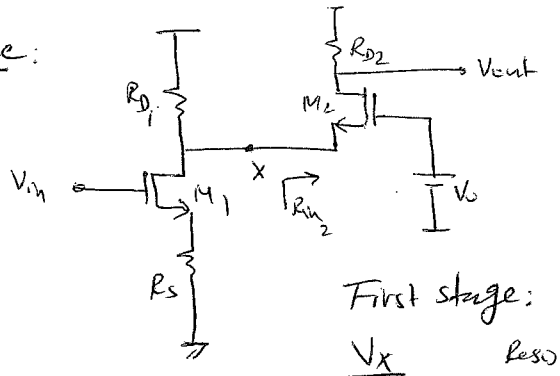




for $\lambda = 0$

$$\boxed{R_{out} = R_D}$$

Example:



$\lambda = 0$

Find $A_v = \frac{v_{in}}{V_{out}}$

$\frac{v_o}{v_{in}} = \frac{V_x}{v_{in}} \times \frac{V_{out}}{v_x}$

First stage: degeneration CS:-

$\frac{V_x}{V_{in}} = \frac{\text{Resistance Connected 2D and ac gnd}}{1/g_m + \text{Resistance Connected 2S and ac gnd}}$

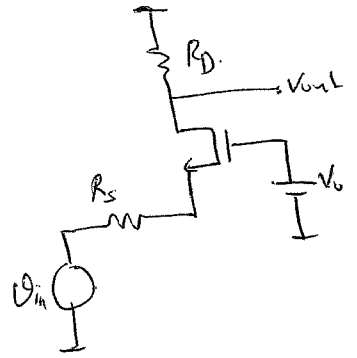
$\frac{V_x}{V_{in}} = -\frac{(R_{D1} \parallel 1/g_{m2})}{1/g_{m1} + R_S}$

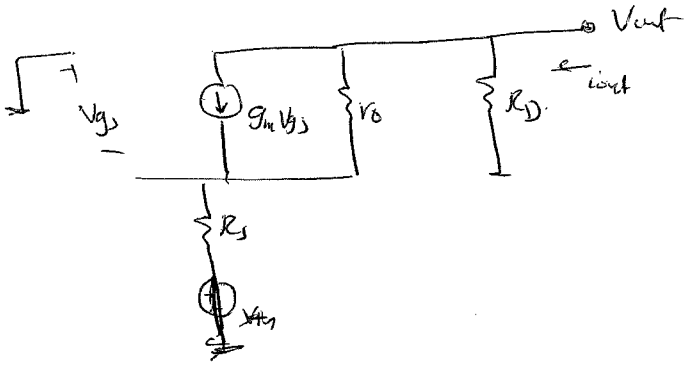
$\frac{V_{out}}{V_x} = g_{m2} R_{D2}$

$\Rightarrow \boxed{A_v = -\frac{g_{m2} R_{D2} (R_{D1} \parallel 1/g_{m2})}{1/g_{m1} + R_S}}$

Output Resistance of CG stage in a special case :-

Find Rout :- for $\lambda \neq 0$



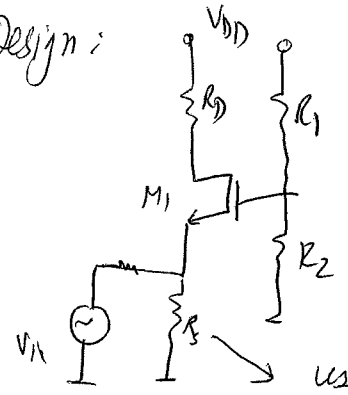


For Rout we set $v_{in} = 0$

The circuit becomes as CS with degeneration

$$R_{out} = R_D \parallel [(1 + g_m r_o) R_S + r_o]$$

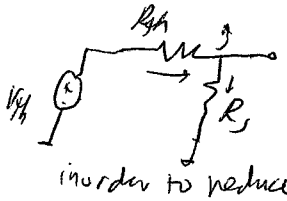
Bias Design:



R_S is used for Biasing

use this resistance inorder the current flows in dc

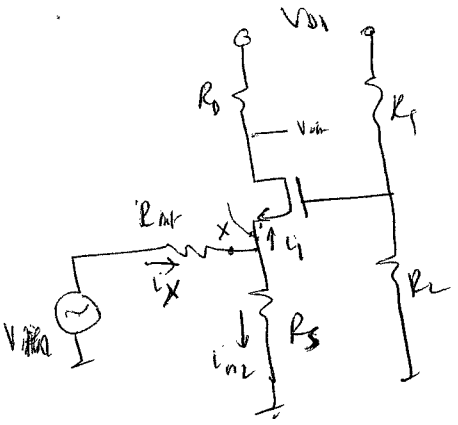
Assuming V_{in} is not ideal can be modeled by V_{th} and R_{th}



inorder to reduce the wase current

$R_S >> R_{th}$

$R_S \cong 10\, R_S$



$$i_1 = \frac{R_S}{R_S + 1/g_m} i_X$$

in order the current flows i_X to transistor

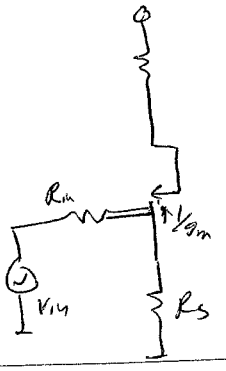
$$i_X = i_1$$

$$\Rightarrow R_S \gg 1/g_m$$

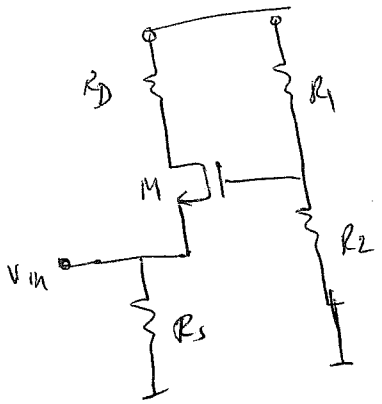
To find A_v

$$\frac{V_{out}}{V_{in}} = \frac{V_x}{V_{in}} * \frac{V_{out}}{V_x}$$

$$\frac{V_{out}}{V_{in}} = \frac{1/g_m \,||\, R_S}{1/g_m \,||\, R_S + R_{in}} * g_m R_D$$



Example: Design CG amplifier $V_{DD} = 1.5\,V$ $P = 1.5\,mW$ $\mu_n C_{ox} = 100\,\mu A/V^2$ $V_{TH} = 0.5\,V$ $\lambda = 0$ $W/L = 50$



$$I_D \cong \frac{P}{V} = 1\,mA$$

$$I_D = \tfrac{1}{2}\mu_n C_{ox} \frac{W}{L}\left[V_{GS} - V_{TH}\right]^2$$

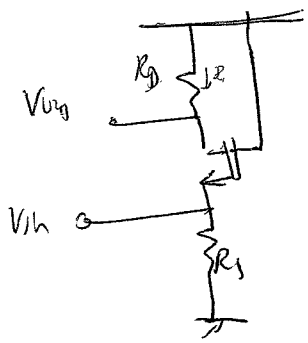
$$\Rightarrow \left(V_{GS} - V_{TH} \geq 0.63\,V \right) \Rightarrow V_{GS} = 1.13\,V$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TH}} = 3.2\,mS = \frac{1}{316\,\Omega}$$

~~We see that $R_S \gg 1/g_m$~~

~~select $R_S \cong 10\,1/g_m = 3.16\,k\Omega$~~

$$R_{S\,max} \cong \frac{V_{DD} - 0.63}{1\,mA} = 370\,\Omega$$



In order to keep M @ saturation

$$I_D R_D \ll V_{TH} \Rightarrow \boxed{R_D = 500\,\Omega}$$

$$A_0 = g_m R_D = 1.6$$

If $W/L = 100$ (Double W/L) $\Rightarrow$ MOS becomes slower

$V_{GS} = 0.947\,V = 0.95\,V$

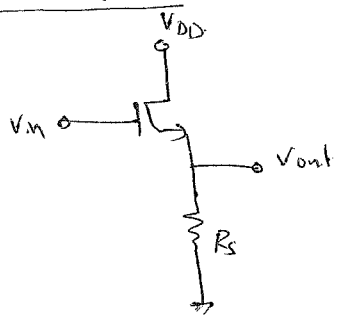
$$R_S = \frac{V_{DD} - V_{GS}}{I_D} = 550\,\Omega \qquad g_m = 4.5\,mS = \frac{1}{220\,\Omega}$$

$A_0 = g_m R_D = 2.3$

lect 41

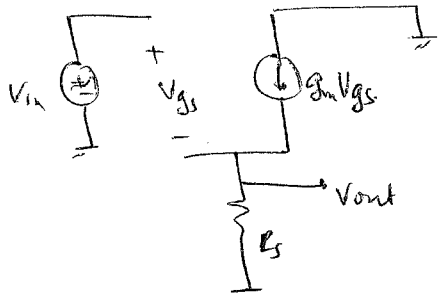
Today's Lect.
- Source Follower
  - Small Signal Analysis
  - Bias Design.

Source Follower:



Input is applied to Gate
Output is taken from the source.

$\lambda = 0$:



KVL:-

$$V_{in} = V_{gs} + R_S (g_m V_{gs})$$
$$= V_{gs}[1 + R_S g_m] \Rightarrow V_{gs} = \frac{V_{in}}{1 + R_S g_m}$$
$$V_{out} = R_S g_m V_{gs}$$
$$= \frac{R_S g_m V_{in}}{1 + R_S g_m}$$
$$A_v = \frac{R_S g_m}{1 + R_S g_m} \leq 1$$

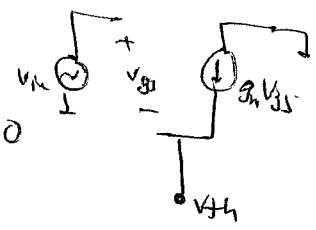
$$\Rightarrow A_v = \frac{R_S}{1/g_m + R_S}$$

$$= \frac{\text{Resistance connected between S and ac gnd}}{1/g_m + \text{Resistance connected between S and gnd}}$$

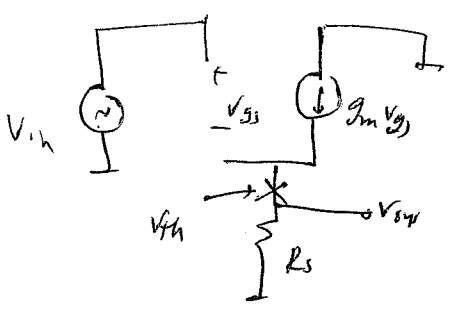
Another technique :

Thevenin equivalent

To Calculate V_{TH} :
- Remove R_S

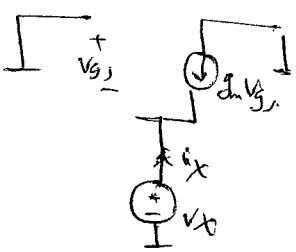


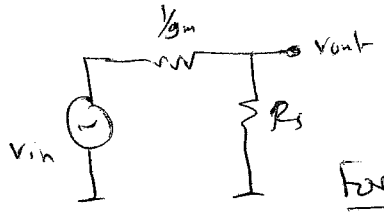
$$g_m V_{gs} = 0 \Rightarrow V_{gs} = 0$$
$$V_{TH} = V_{in}$$



- R_{TH} :-

$$V_X = -V_{gs1}$$
$$i_X + g_m V_{gs} = 0$$
$$i_X - g_m V_X = 0$$
$$R_X = V_X / i_X = \frac{1}{g_m}$$

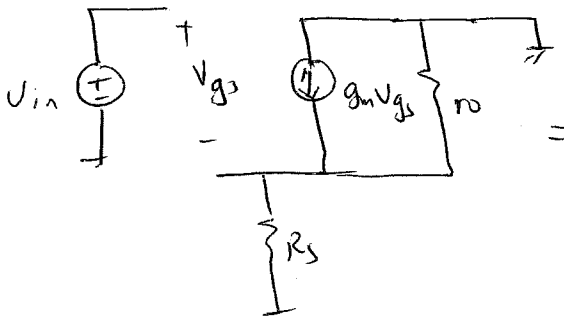


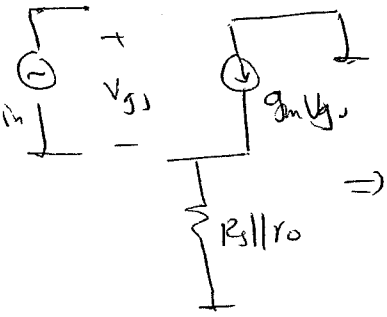


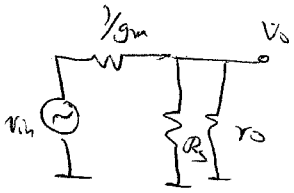
$$A_v = \frac{R_S}{R_S + 1/g_m}$$

(21)

For $\lambda \neq 0$



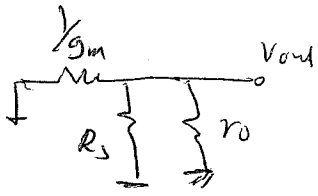




$$A_v = \frac{R_S \| r_O}{R_S \| r_O + 1/g_m}$$

Calculate Rin

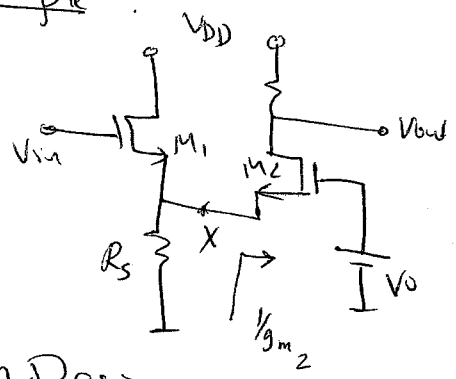
@ low frequency $R_{in} = \infty$



Calculate Rout

$$R_{out} = \left.\frac{V_{out}}{i_{out}}\right|_{V_{in}=0} = 1/g_m \| R_S \| r_O$$

Example :



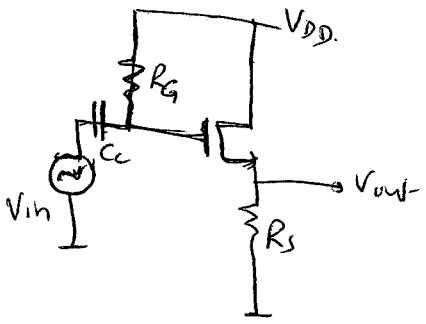
$\lambda = 0$.

$$A_v = \frac{V_x}{V_{in}} * \frac{V_{out}}{V_x}$$

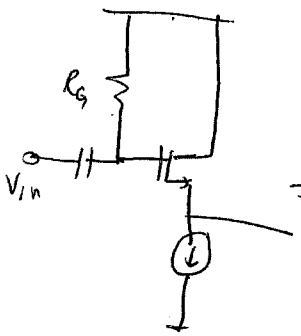
$$\frac{V_x}{V_{in}} = \frac{R_S \| 1/g_{m2}}{R_S \| 1/g_{m2} + 1/g_{m1}}$$ (Source follow

$$\frac{V_{out}}{V_x} = g_{m2} R_D$$ (Common gate

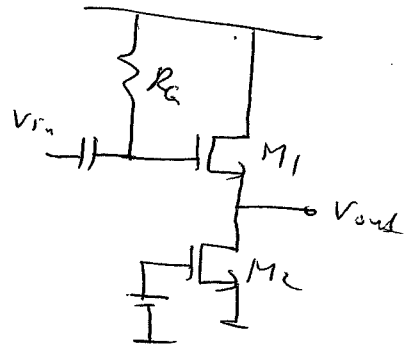
Bias Design.



OR

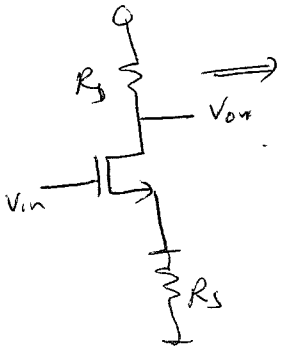


=>

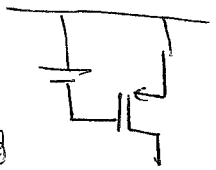


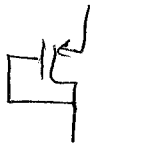
Summery

CS stage



load { Resolive
Current source
diode Connected

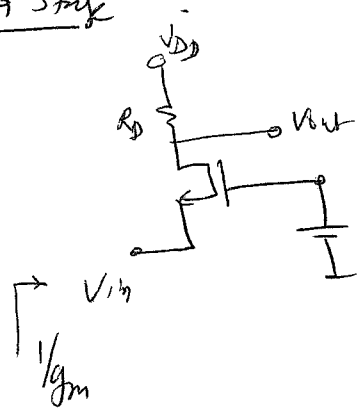

Current source


Diode

$$A_v = -\frac{R_D}{1/g_m + R_S}$$

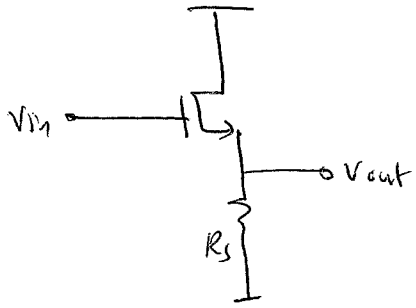
$$R_{out} = R_D \| \left[r_o + R_S(1 + g_m r_o) \right]$$

CG stage



$$A_v = g_m R_D$$

Source follower



$\lambda = 0$

$$A_v = \frac{R_S}{R_S + 1/g_m}$$

$$R_{out} = 1/g_m \| R_S$$