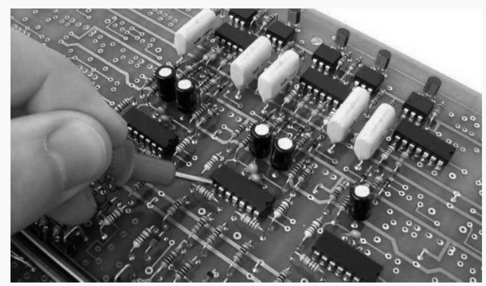
Electronic Circuits 1

ENEE 2303

Mr. Mohammad AL-Jubeh

Electronic Circuits

- We encounter electronics in our daily life in form of telephones, radios, television, audio equipment, home appliances, computer and equipment for industrial control and automation .

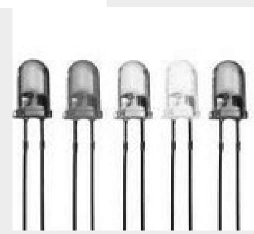
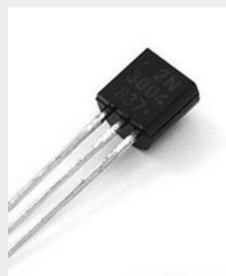
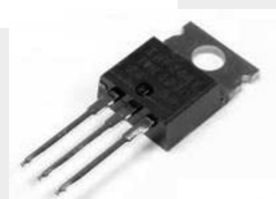


- The field of electronics deals with the design and applications of electronic devices .

Electronics Devices

- Diodes
  - a) Rectifier diode
  - b) Zener diode
  - c) Light Emitting Diode (LED)
- Transistors
  - a) Bipolar Junction Transistor (BJT)
  - b) Field Effect Transistor (FET)
- Integrated Circuit (IC)

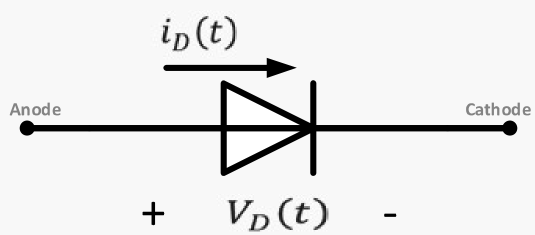


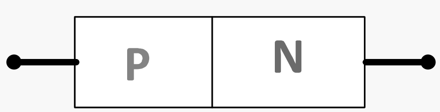

Diode

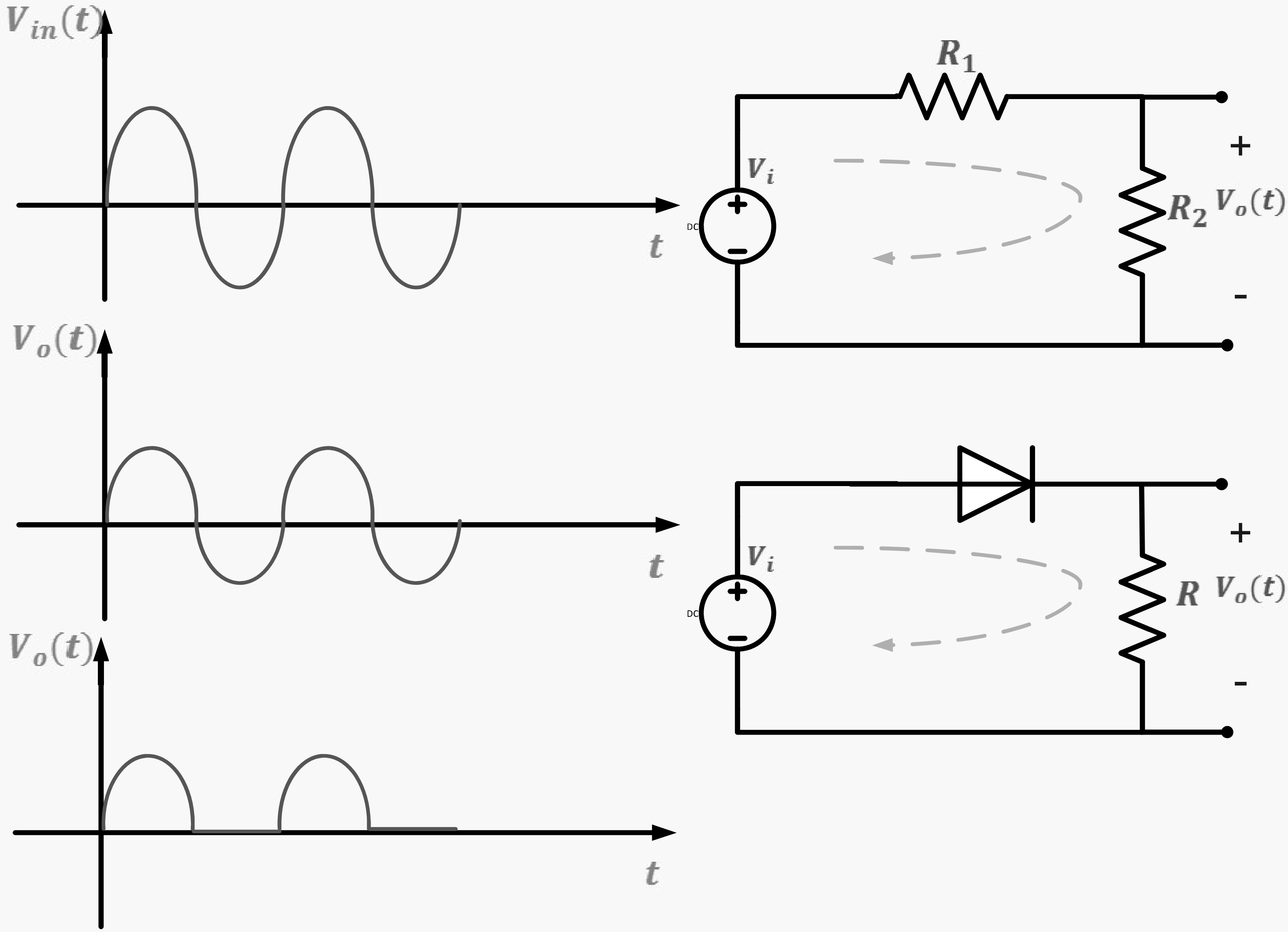
- It is an electronic device with a single p-n junction and it has the ability to conduct current in one direction while blocking current in the other direction.

- Circuit Symbol :



- Physical construction



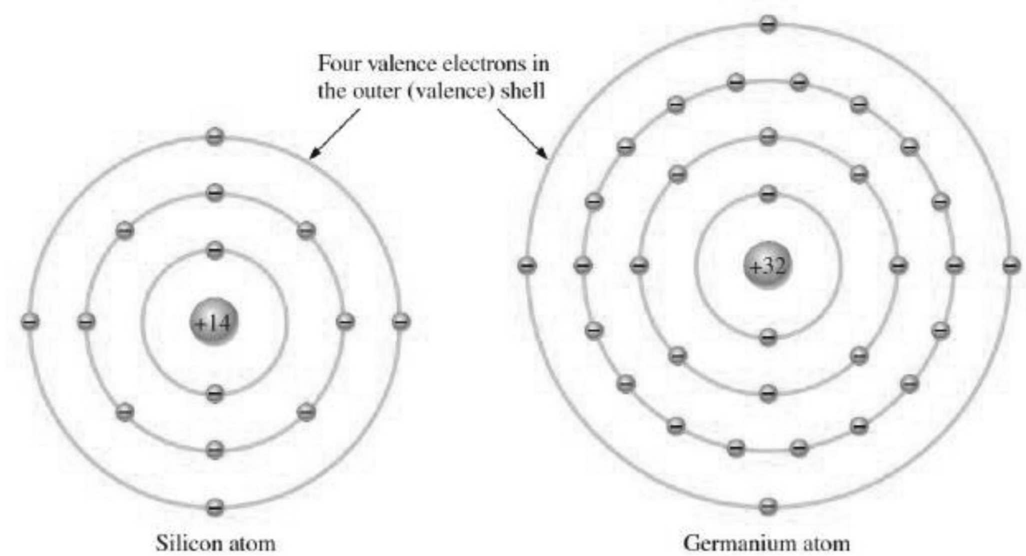

$V_{in}(t)$
t
$V_o(t)$
t
$V_o(t)$
t
R_1
V_i
DC
R_2
+
$V_o(t)$
-
V_i
DC
R
+
$V_o(t)$
-

Semiconductor

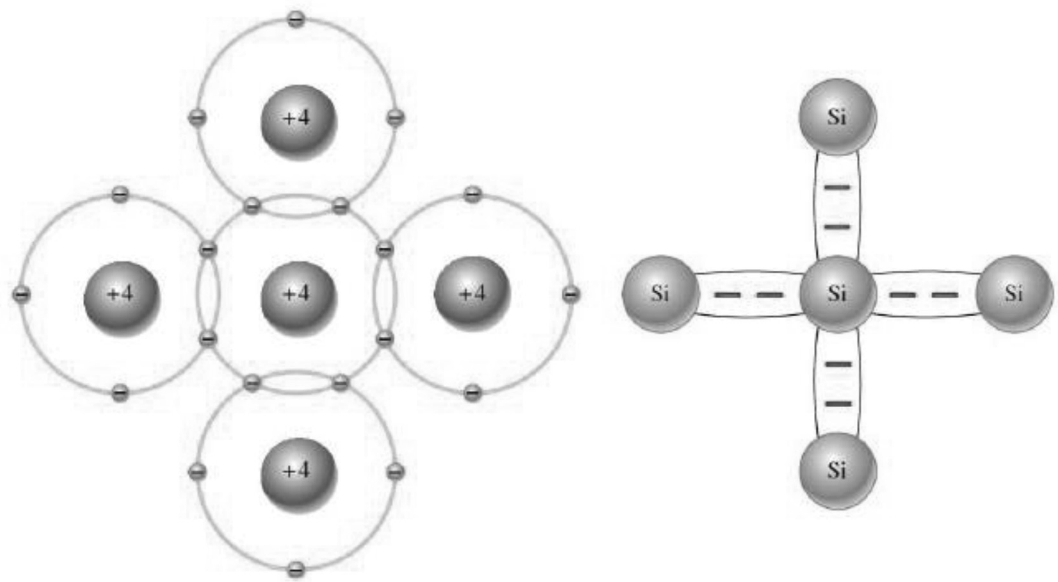
- Electronic devices such as diodes, transistors and integrated circuits are made of a semiconductor material .

- Semiconductors : materials whose resistance lies between low resistance of conductor and the high resistance of insulator .

Atomic structure

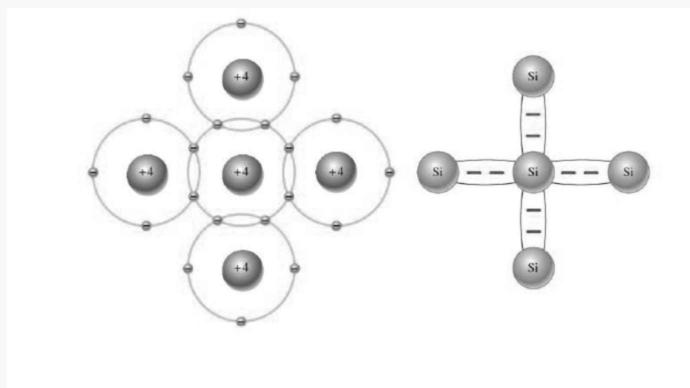


Covalent bond



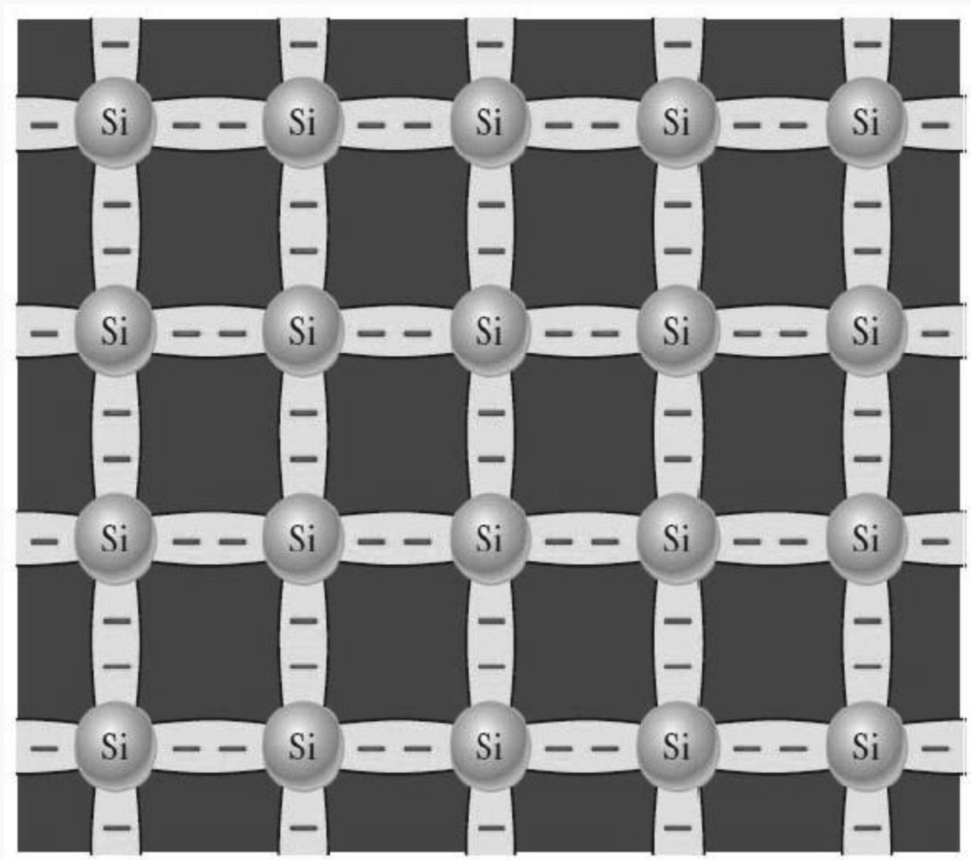
Covalent bond

- A silicon (Si) atom with its four valence electrons shares an electron with each of its four neighbors
- This effectively creates eight shared valence electrons for each atom and produces a state of chemical stability .
- Also, this sharing of valence electrons produce the covalent bonds that hold the atom together; each valence electron is attracted equally by the two adjacent atoms which share it .



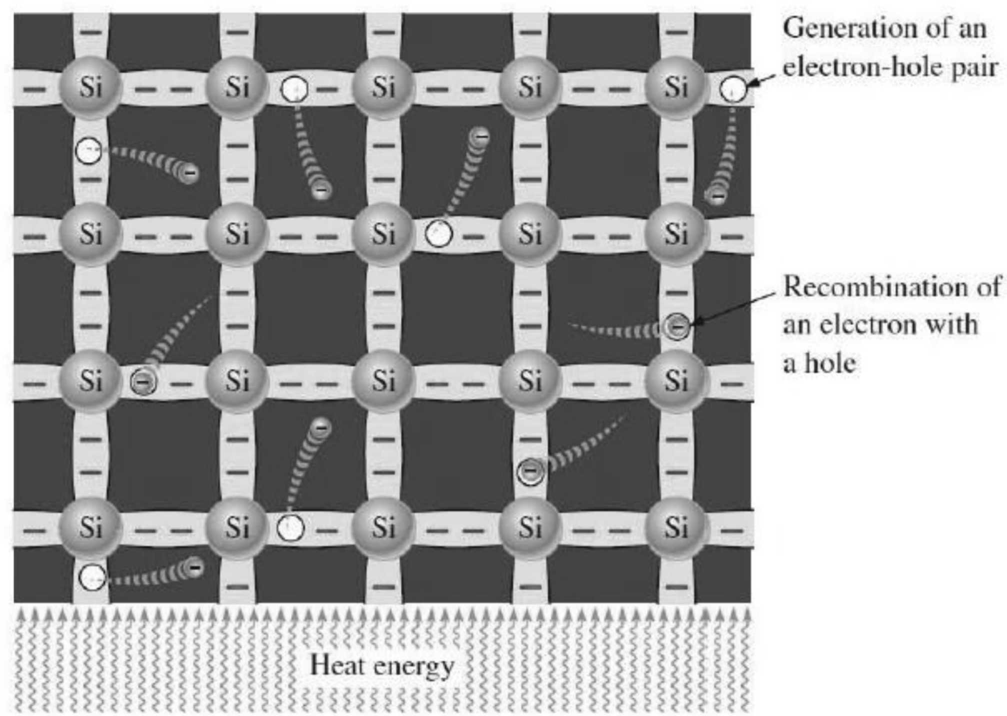
Covalent bond in silicon crystals

- At absolute zero degree (-273 C^o) all valence electrons are tightly bonded to their atoms and there is no free electrons, so the silicon behave as an insulator .



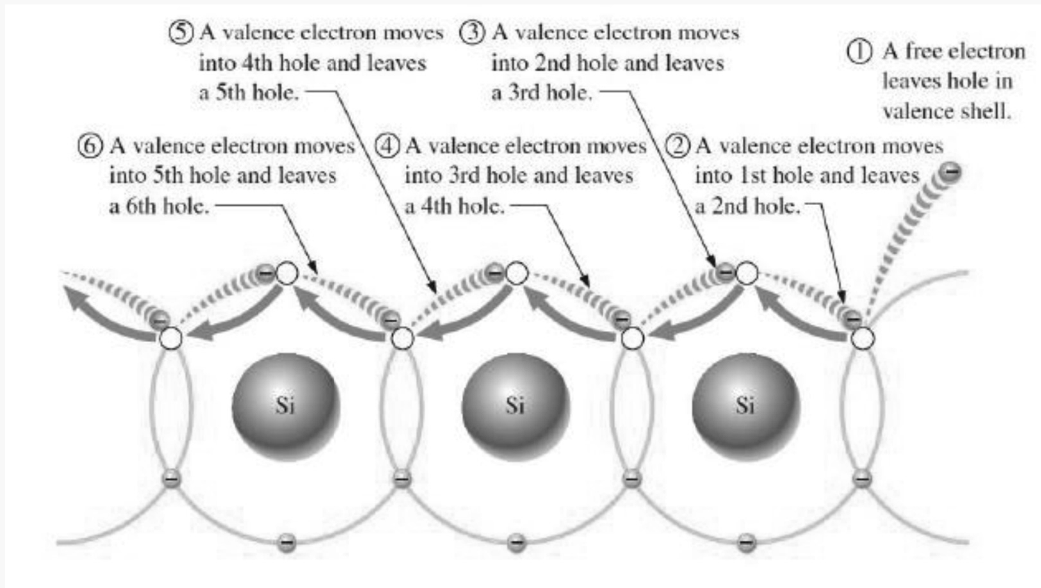
Rupture of the a covalent bond

- When an electron becomes free that is unattached to any atom, a vacancy is left in the valence band within the crystal . This vacancy is called hole .
- For every free electron, there is one hole .
- One broken covalent bond → one free electron + one hole
- At room temperature there is one broken covalent bond for every $3x10^{12}$ pure Si atoms .
- At room temperature there are few available charge carriers (free electrons + holes)

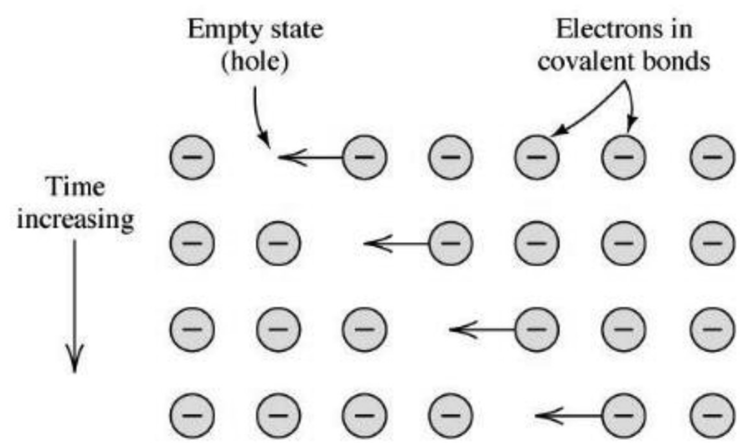


Hole motion

- When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left.



Holes movement



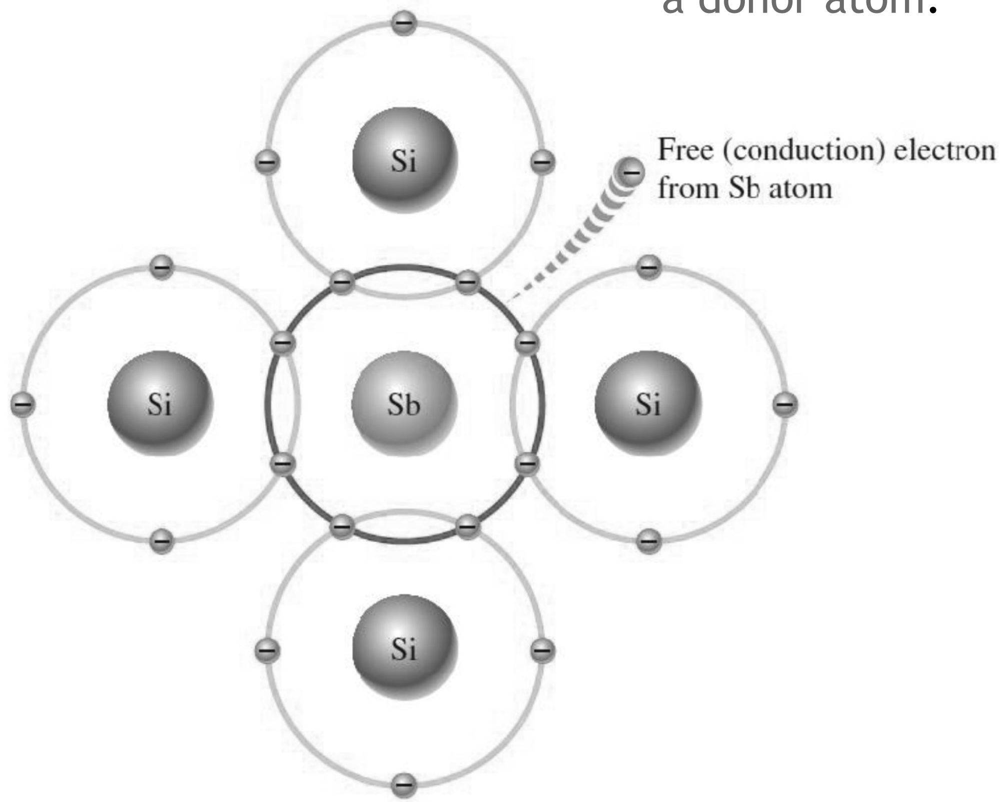
Doping

- A manufacturing process that adds free charge carriers (free electronic or hole) into a pure semiconductor material to increase its conductivity .

- Doping → n-type or p-type material

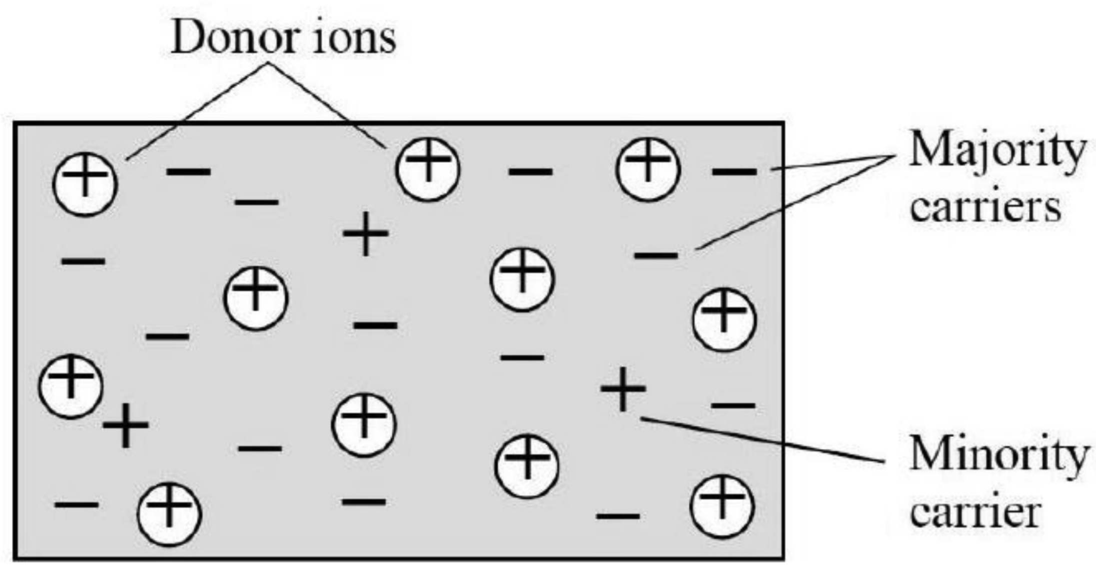
N - type semiconductor

Sb (antimony) has five valence electrons and it is called
a donor atom.



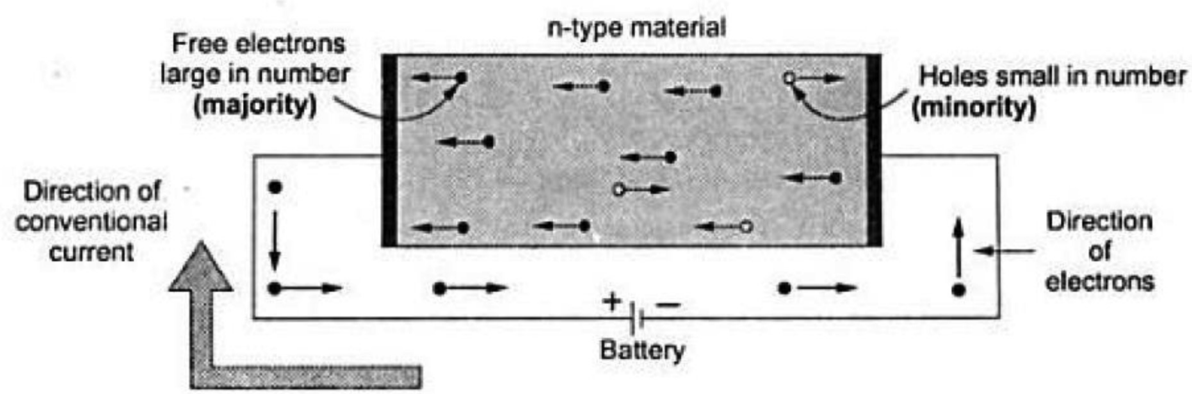
- Sb (antimony) has five valence electrons and it is called a donor atom.

In the n-type material the free electrons are the majority and the holes are the minority.



n-type

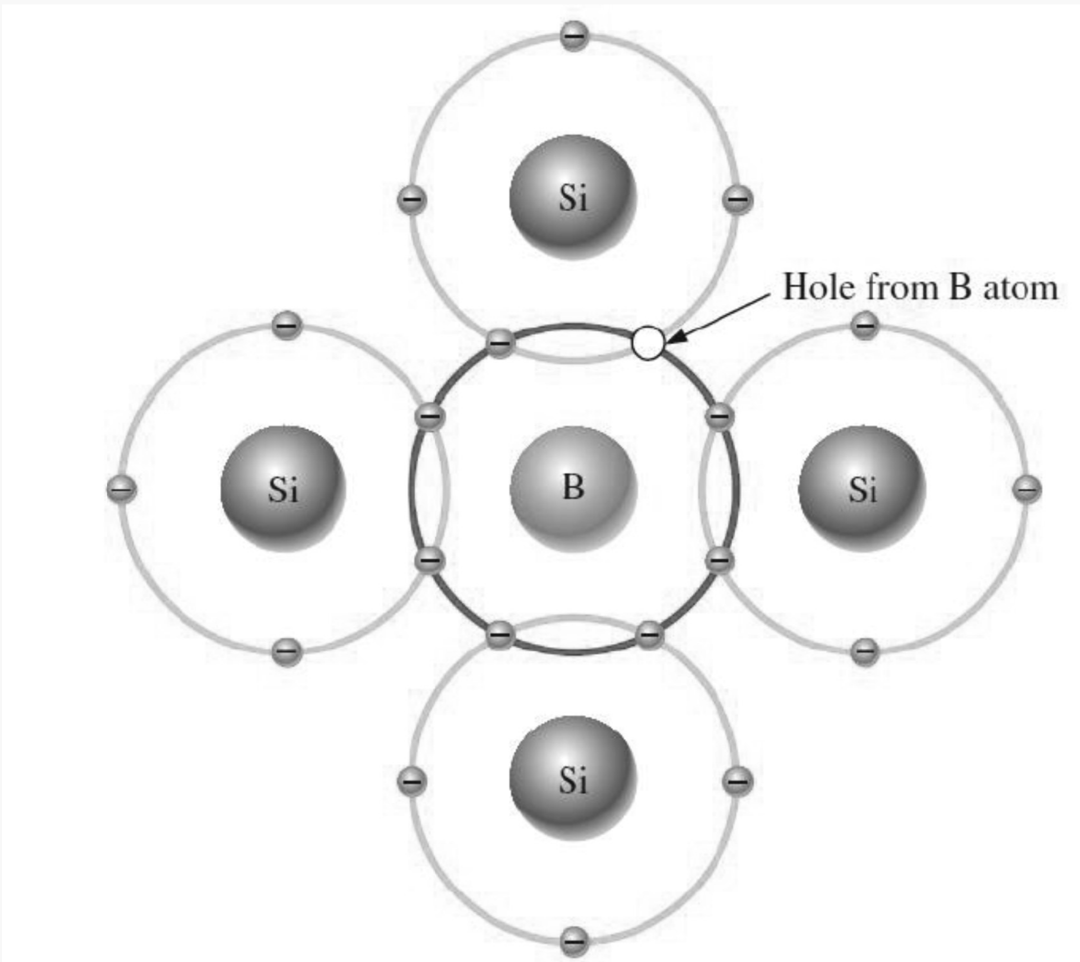
Conduction in n-type material



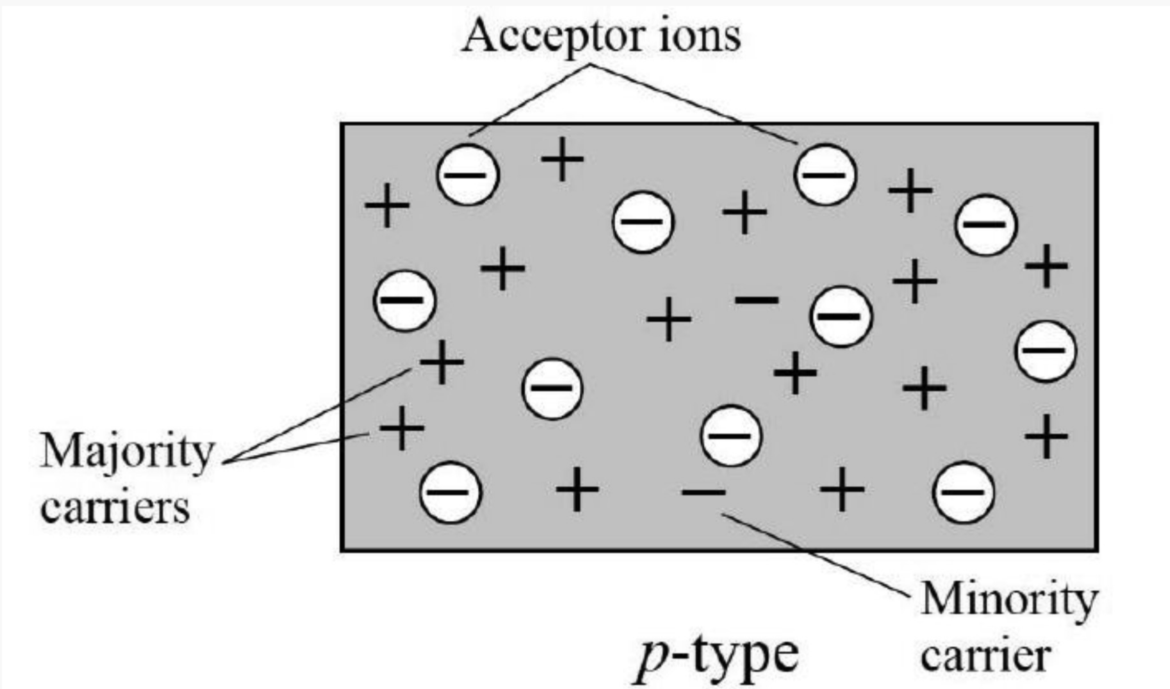
Conduction in n-type material

P - type semiconductor

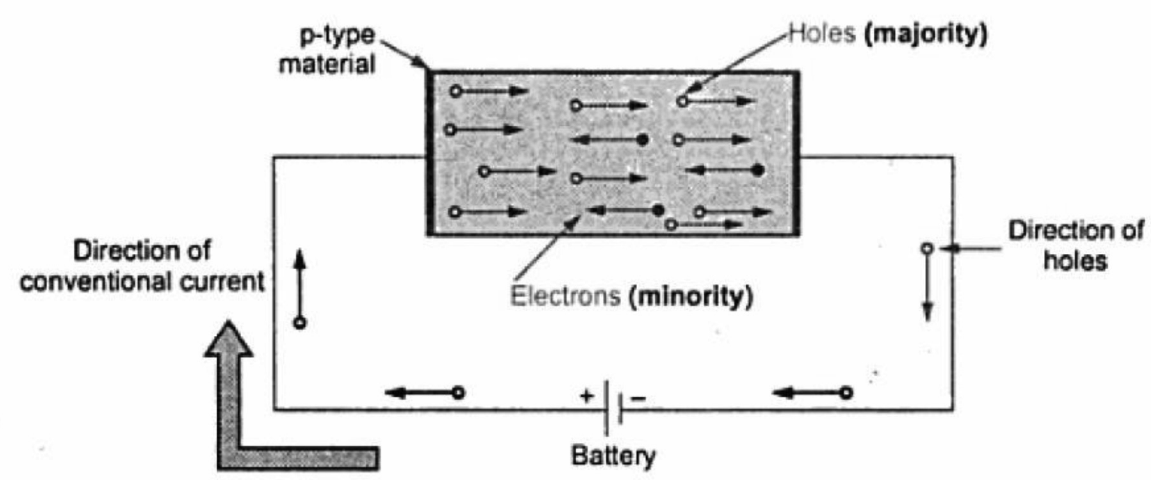
B (Boron) has three valence electrons (acceptor atom)



► B (Boron) has three valence electrons (acceptor atom)
In the p-type material the holes are the majority and the free electrons are the minority .



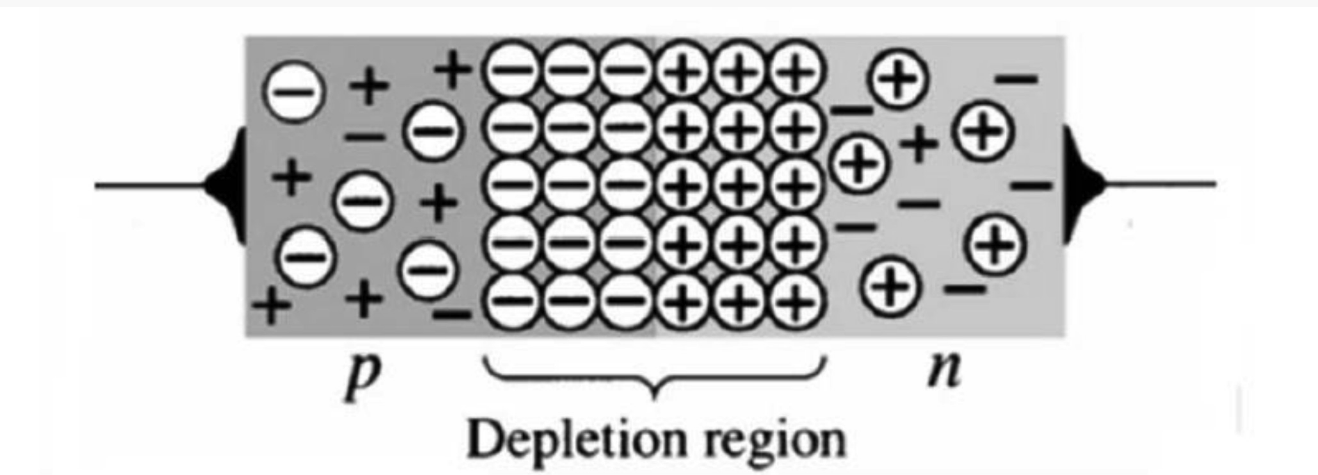
Conduction in p-type material



Conduction in p-type material

Pn junction

- The p-n junction is the basis for diodes, certain transistors ,and other devices.



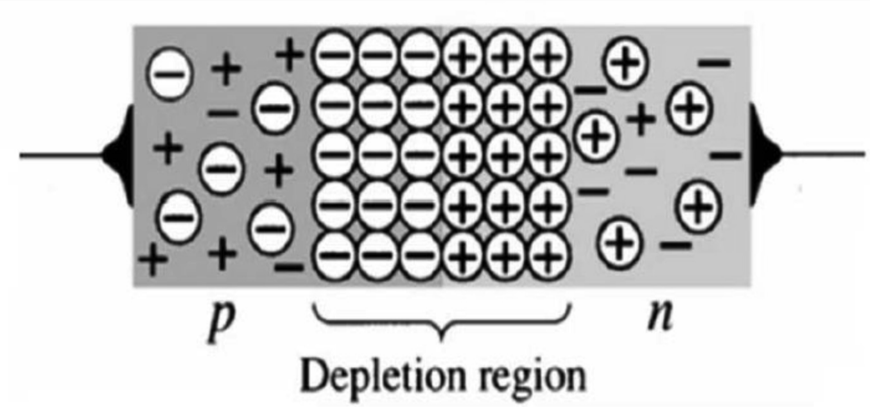
1) Electrons from the n-type material near the junction diffuse a cross the junction.

2) These electrons fill the holes in the p-type material adjacent to the junction.

3) As a result of electrons leaving the n-type material , donor ions are created on the n side of the junction .

4) When these electrons fill holes in the p side of the junction ,accepter ions are produced.

5) A wall of stationary positive ions is aligned with a wall of negative ions along the n and p sides of the junction .

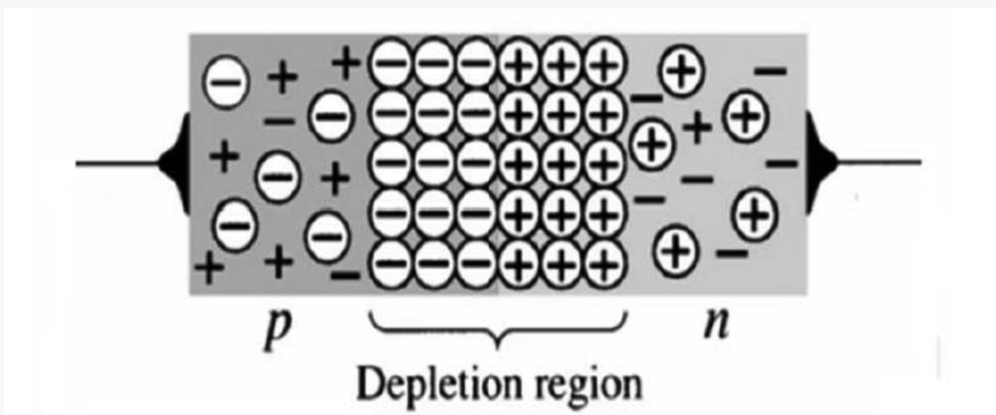


6) The space occupied between the ion walls is called depletion region.

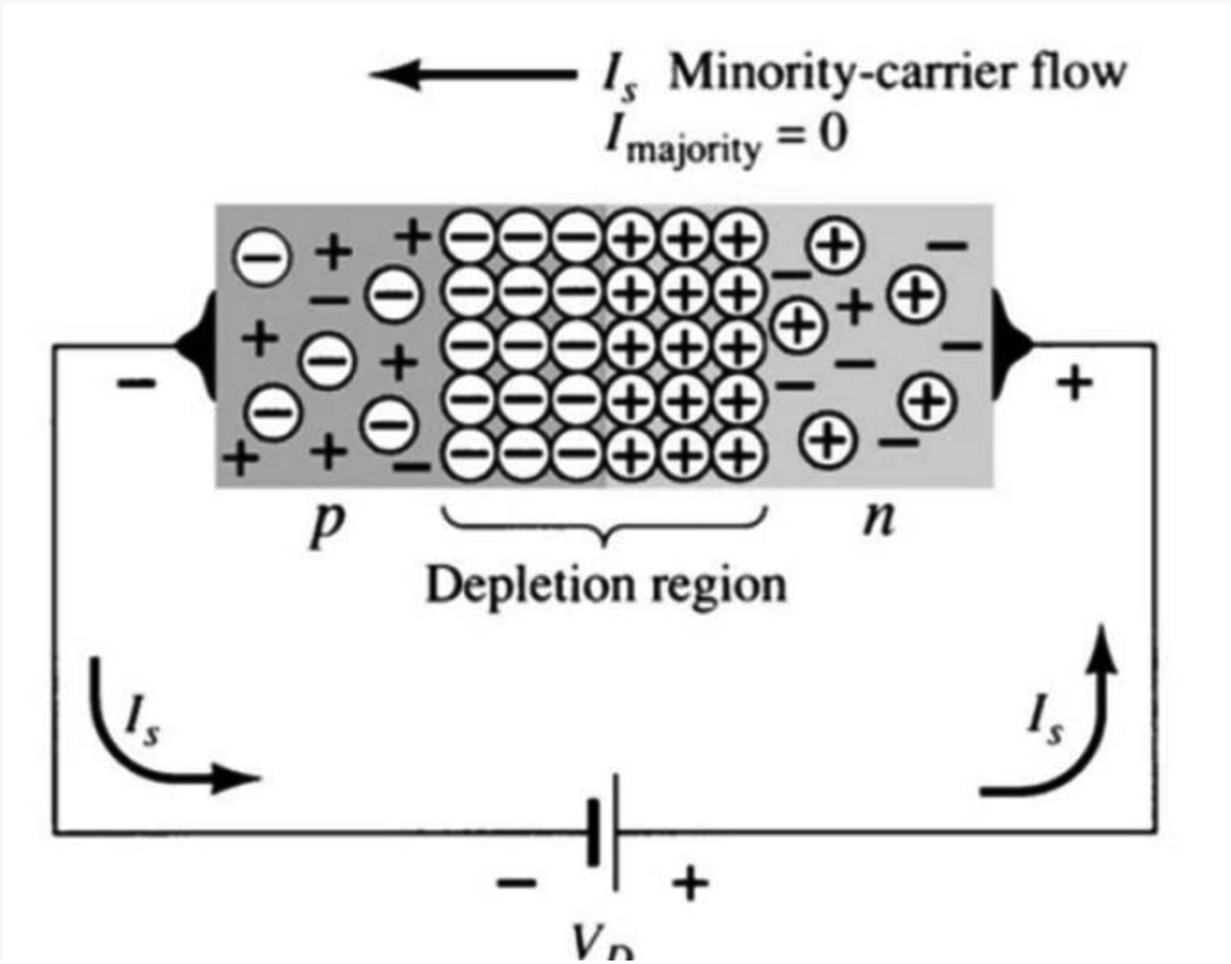
7)Whenever there exists a positive charge with respect to a negative charge , a voltage difference is set between charges ;(Junction potential, Junction barrier).

8) The junction potential acts as potential barrier that tend to prevent majority carriers from crossing the junction.

9) Minority carriers are aided by the junction potential .



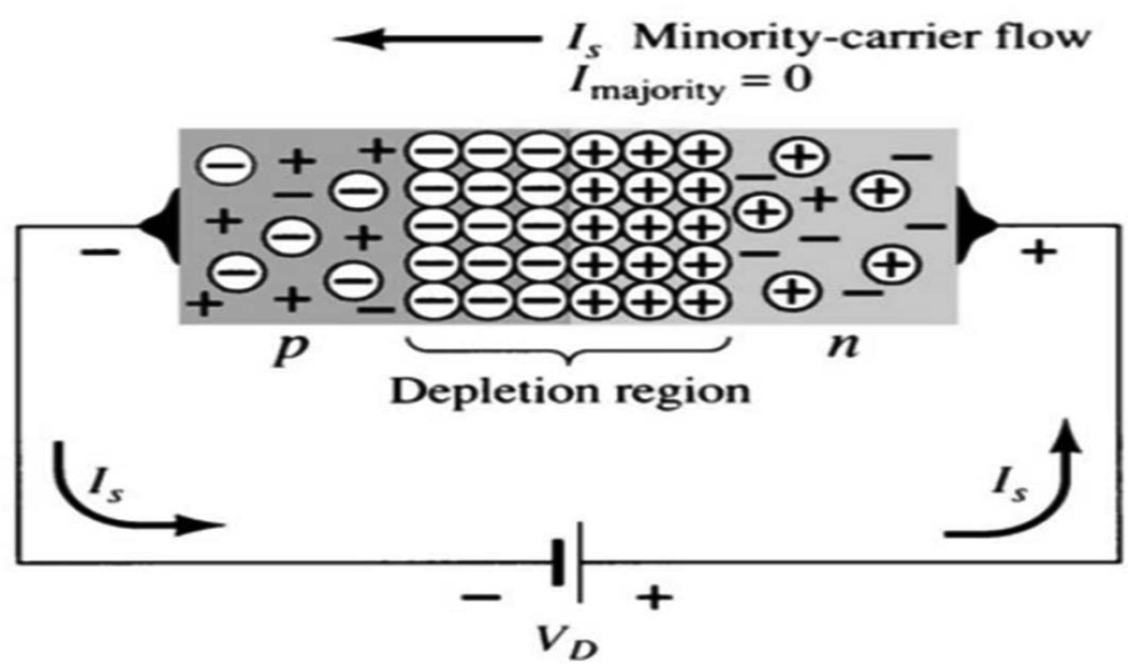
Reverse bias of a pn junction



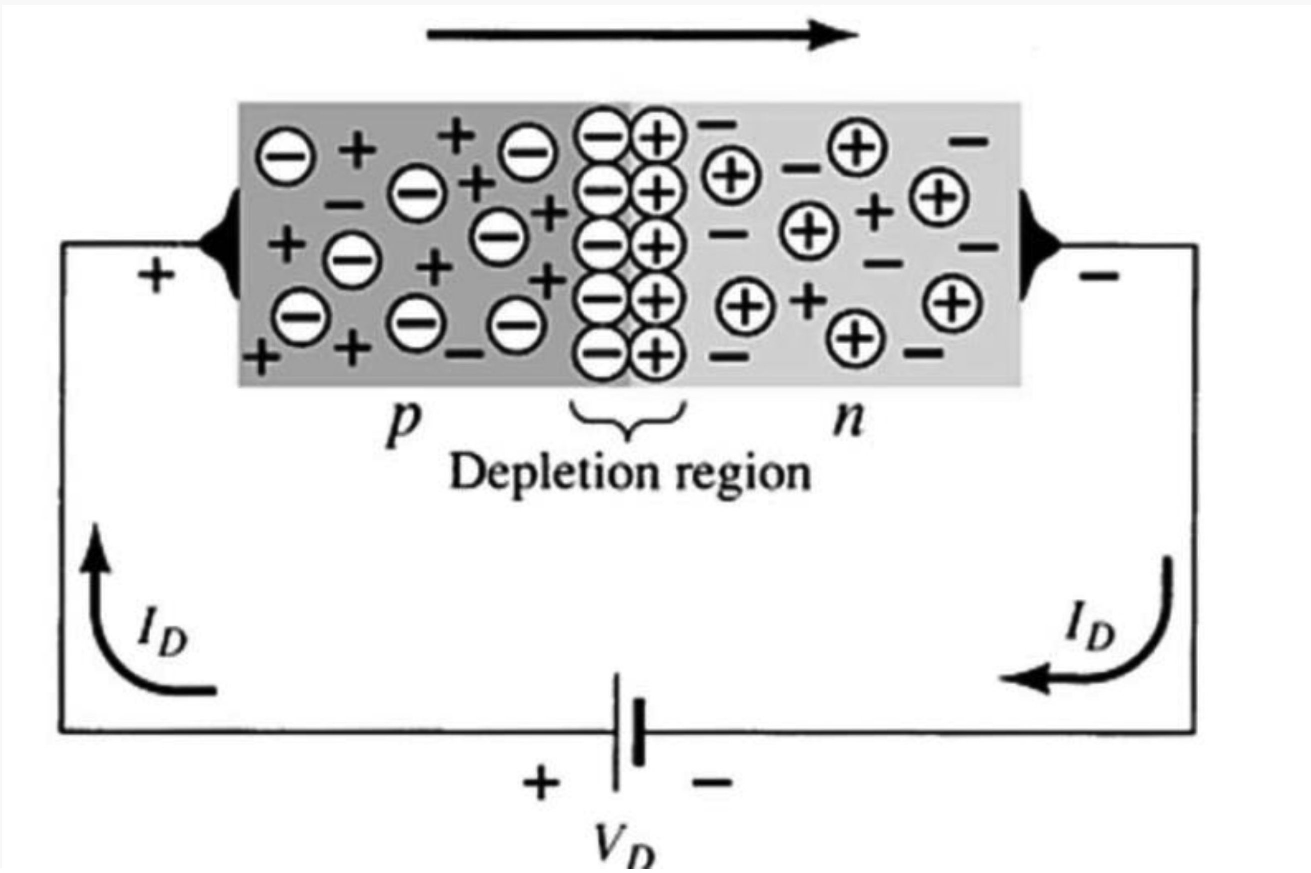
▶ The reverse voltage causes the depletion region to widen .

▶ The electrons in the n-type material are attracted toward the positive terminal of the voltage source .

▶ The holes in the p-type material are attracted toward the negative terminal of the voltage source .



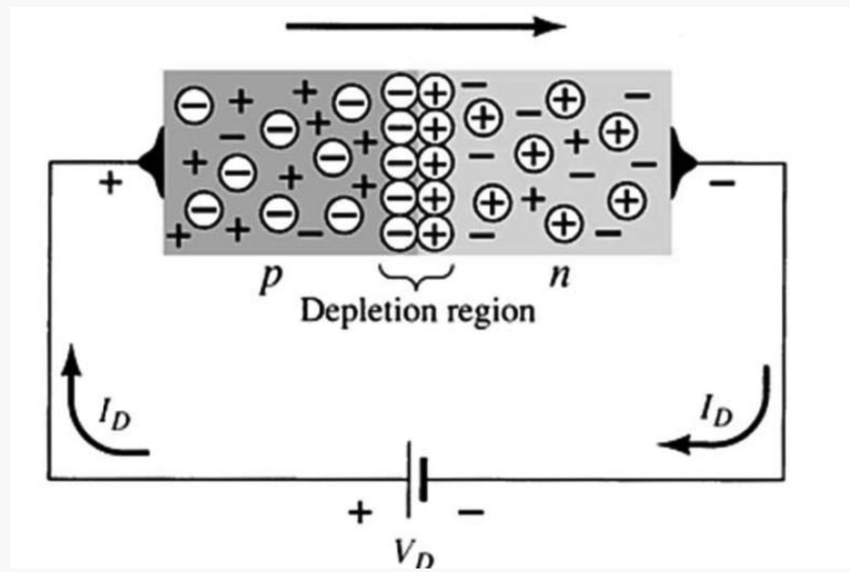
Forward bias of a pn junction



- The forward voltage causes the depletion region to narrow

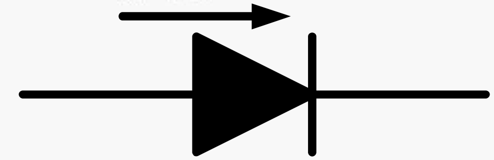
- The electrons and holes are pushed toward the p-n junction

- The electrons and holes have sufficient energy to cross the p-n junction



Diode Equation

$$i_D(t) = I_S(e^{\frac{V_D(t)}{\eta V_T}} - 1)$$



Is: Revers saturation current

Is= 10^{-12}, 10^{-14}A

η : eta

$$\eta = \begin{cases} 1\ for\ Ge \\ 2\ for\ Si\ (small\ current) \\ 1\ for\ Si\ (large\ current) \end{cases}$$

V_T = Thermal Voltage

$V_T = \frac{T}{11600}$;T in kelvin

At Room Temp. T=300k

∴ V_T = 25.69 mv at Room Temp.

$$i_D(t) = I_S(e^{\frac{V_D(t)}{\eta V_T}} - 1)$$

- The equation is a non linear equation

∴ The Diode is non linear Device

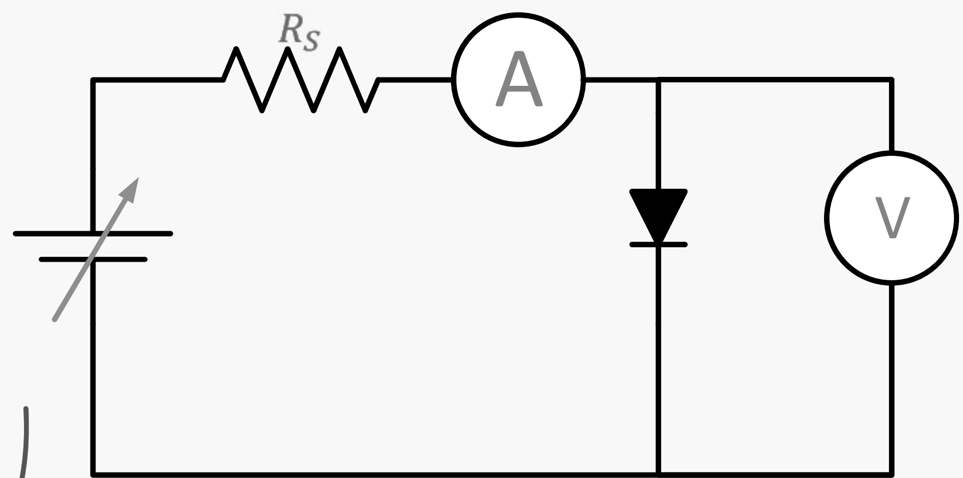
- For positive $V_D(t)$

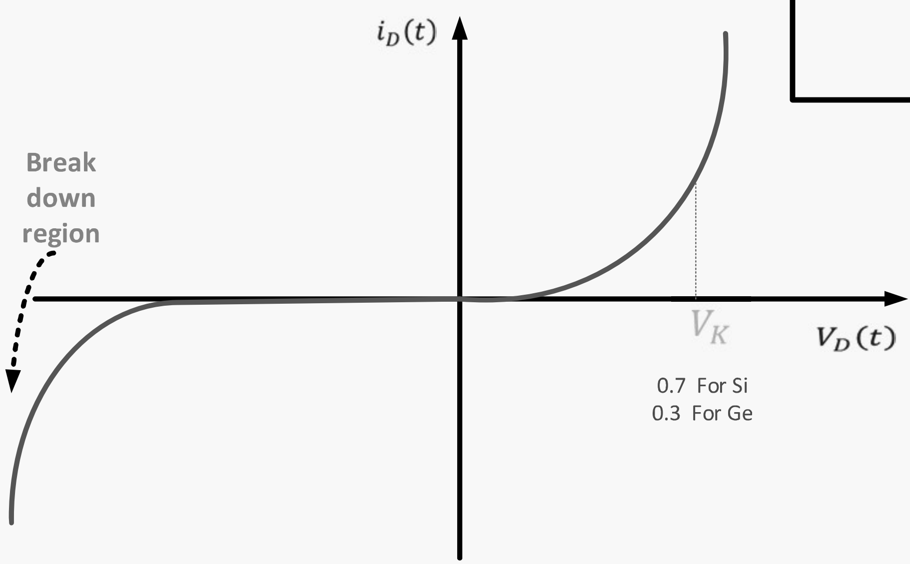
$$i_D(t) = I_S(e^{\frac{V_D(t)}{\eta V_T}})$$

- For negative $V_D(t)$

$$i_D(t) = -I_S$$

Diode V-I Characteristic curve





Approaches to Diode Circuit Analysis

The rectifier diode is a non linear device .

There are essentially three basic approaches to the solution of such problem :

1- The use of non linear mathematics

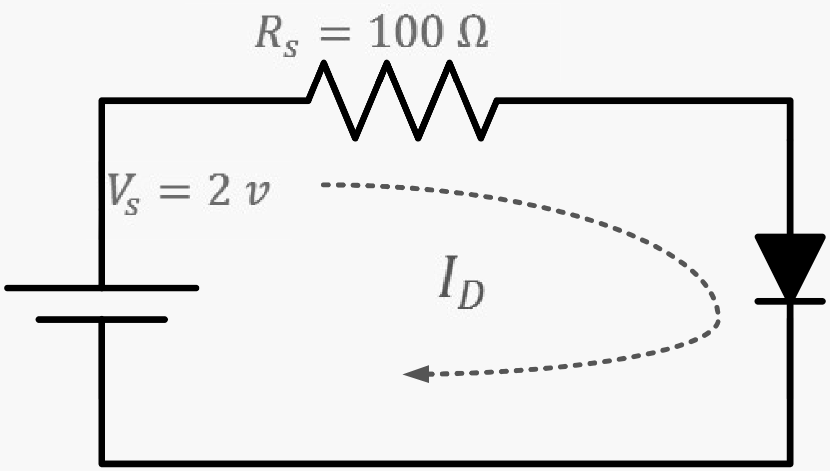
2- The use of graphical techniques

3- The use of equivalent circuit (models)

- Piece wise linear models

1)The use of non linear mathematic

- For the circuit shown, find I_D and V_D



Silicon:
η=1.1
I_S= 10^{-14} A

- KVL : $V_S = R_S I_D + V_D$

$$I_D = I_S(e^{\frac{V_D}{\eta V_T}} - 1)$$

- Since the diode is forward biased , we could approximate

$$I_D = I_S(e^{\frac{V_D}{\eta V_T}})$$

- Solving for $V_D = \eta\, V_T \ln \frac{I_D}{I_S}$

$\therefore$ We have two equations and two unknowns

$V_S = R_S I_D + V_D$ 1

$V_D = \eta V_T \ln \frac{I_D}{I_S}$ 2

$$\therefore \quad V_S = R_S I_D + \eta V_T \ln \frac{I_D}{I_S}$$

- non linear equation

Iterative Analysis

$$I_D = \frac{V_S - V_D}{R_S}$$

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

1) Let $V_D = 0.7$v

   $I_D = \frac{2-0.7}{0.1k}$ = 13 mA

$V_D = 0.7882392$v The error is large

2) Let $V_D = 0.7882392$v

   I_D = 12.117608 mA

$V_D = 0.7862529$v The error is small

3) Let $V_D = 0.7862529$v

$I_D = 12.137471$ mA

$V_D = 0.7862991$v The error getting smaller

4) Let $V_D = 0.7862991$v

$I_D = 12.137009$mA

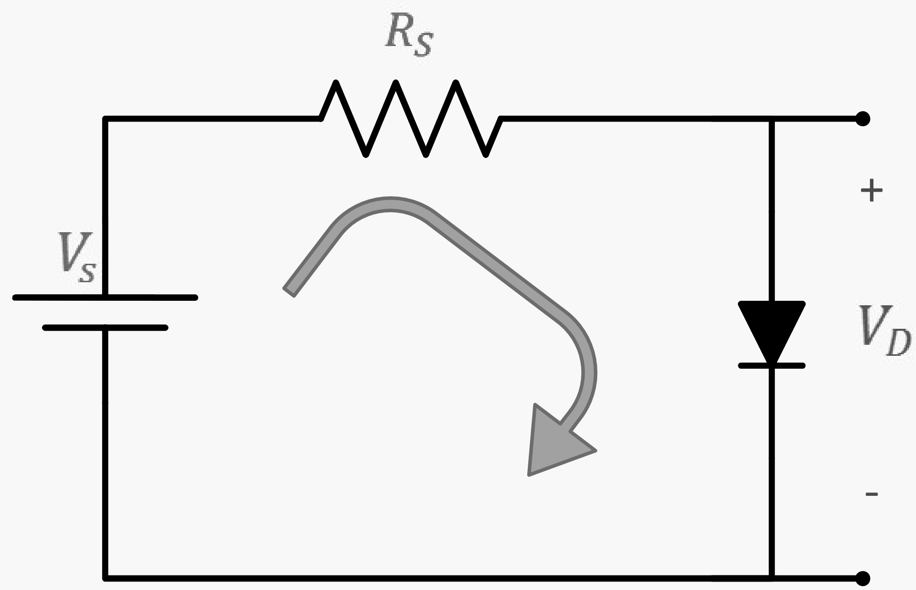
$V_D = 0.786298066$v

$I_D = 12.137$ mA
$V_D = 0.7863$v

2) The use of graphical techniques

$V_S = R_S I_D + V_D$ ………………1

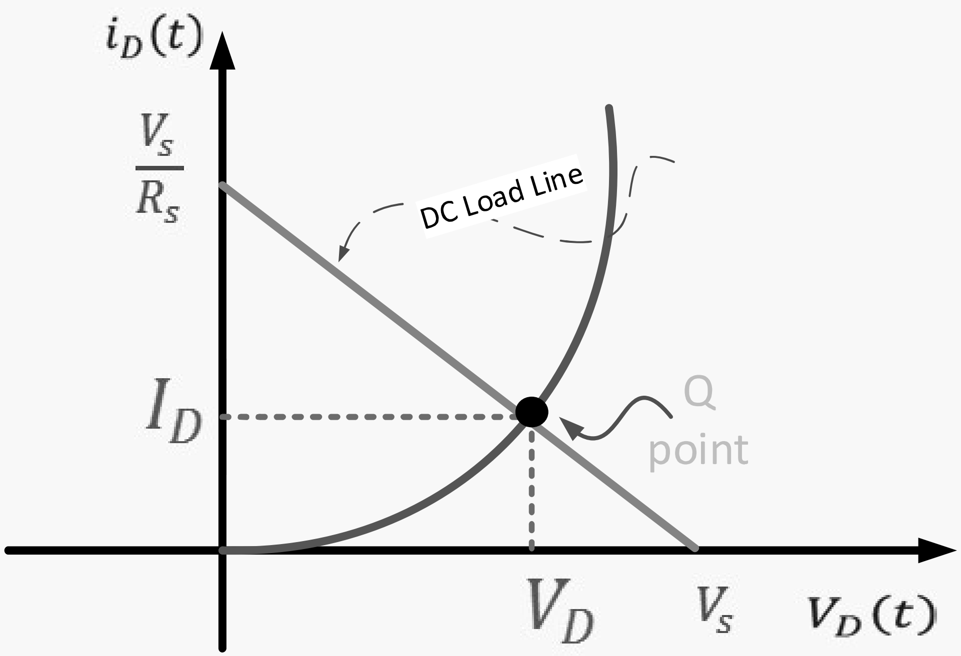
$I_D = I_S\left(e^{\frac{V_D}{\eta V_T}} - 1\right)$ …………2



- Using equation 1

$$I_D = -\frac{1}{R_S}V_D + \frac{V_S}{R_S}$$

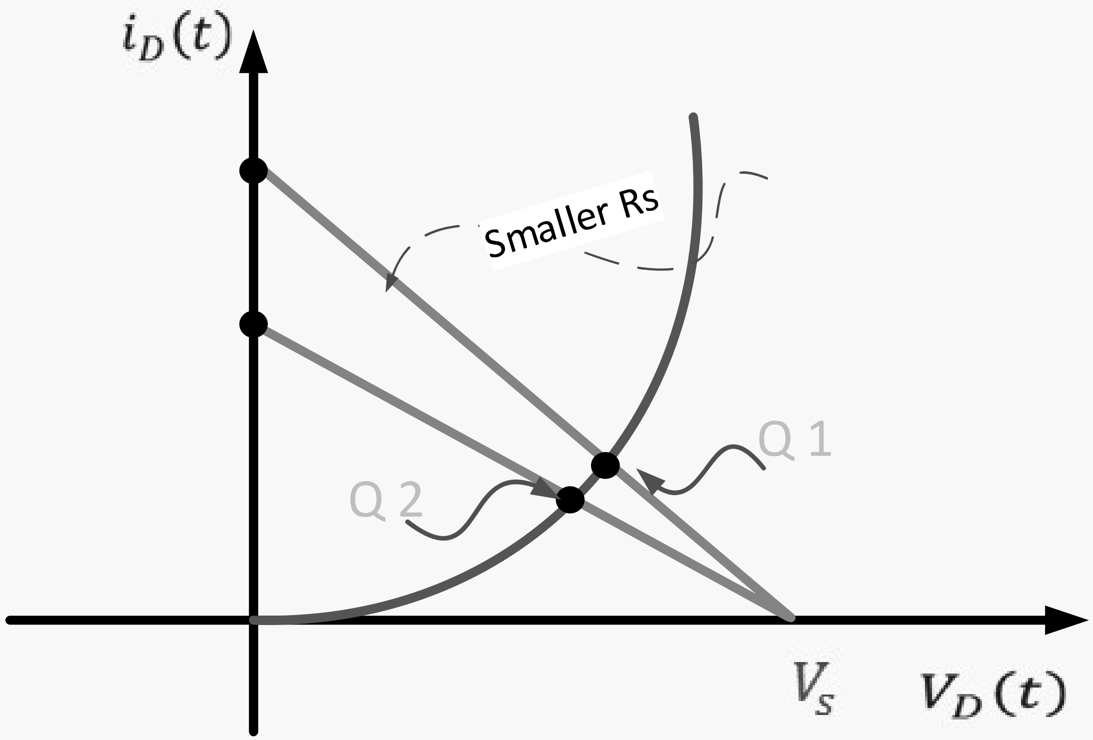
Drawing the two equations



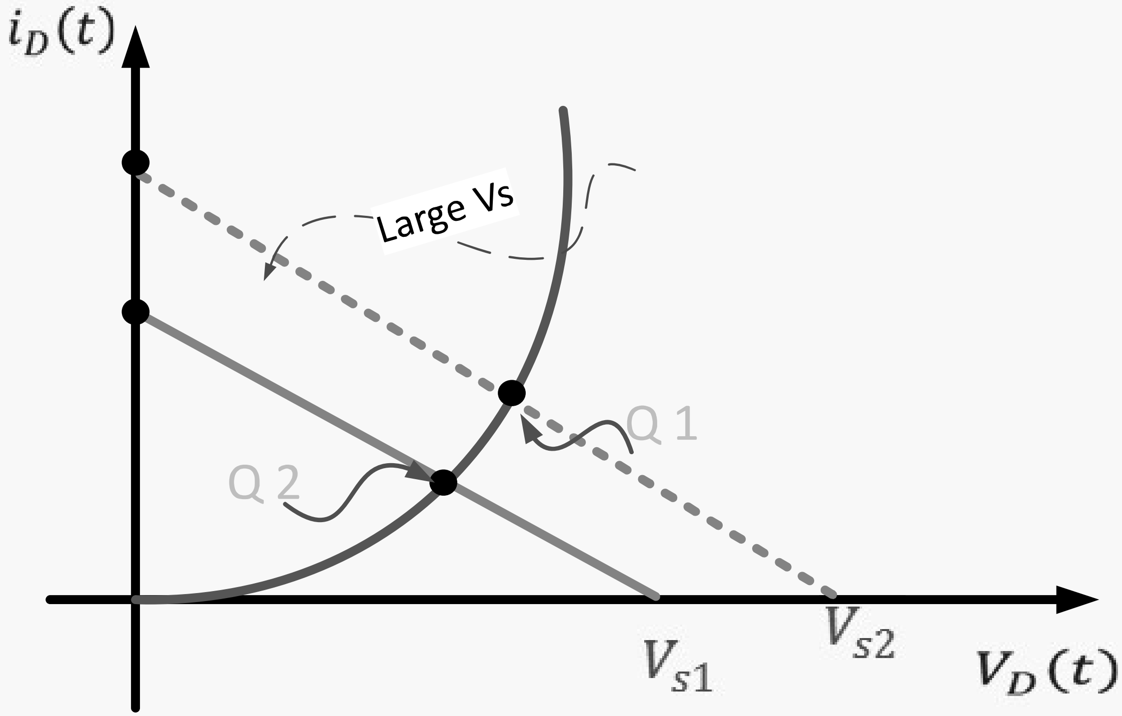
$$I_D = -\frac{1}{R_S} V_D + \frac{V_S}{R_S}$$

- Q point = $(I_{DQ}\ ,\ V_{DQ}) =$ Quiescent point

The effect of Rs on the Qpoint



The effect of Vs on Qpoint



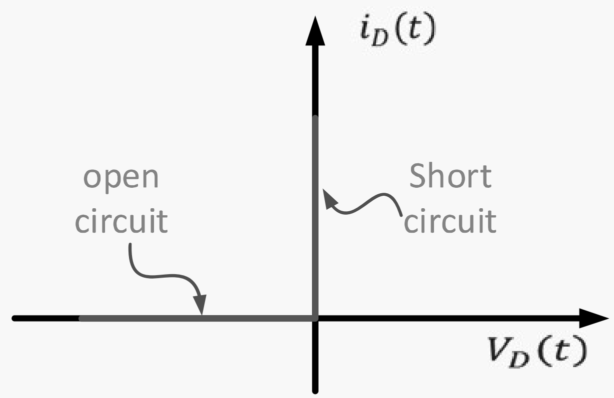
The Use of Diode Model

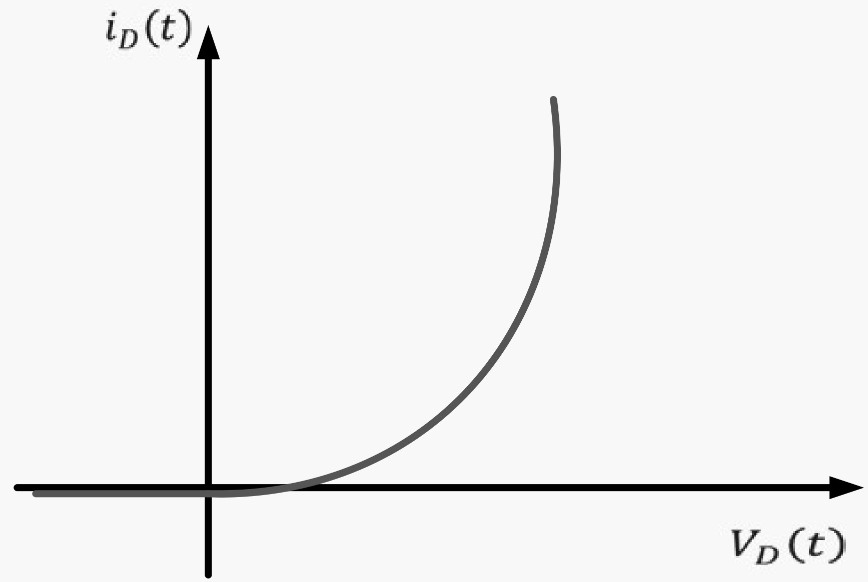
3) The use of models

- A piece wise linear models is an electrical equivalent circuit of a nonlinear electronic device

- It is composed of linear circuit elements arranged to approximate the characteristics of the electronic device .

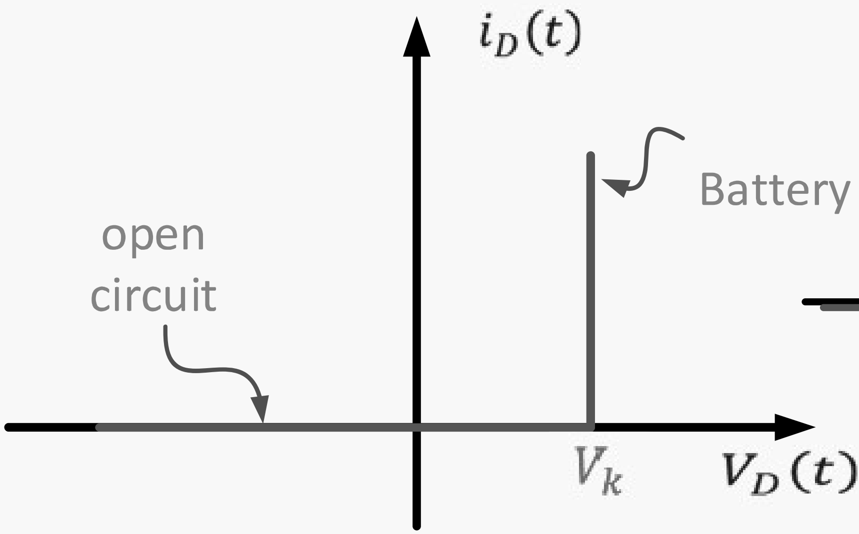
a) ideal diode model

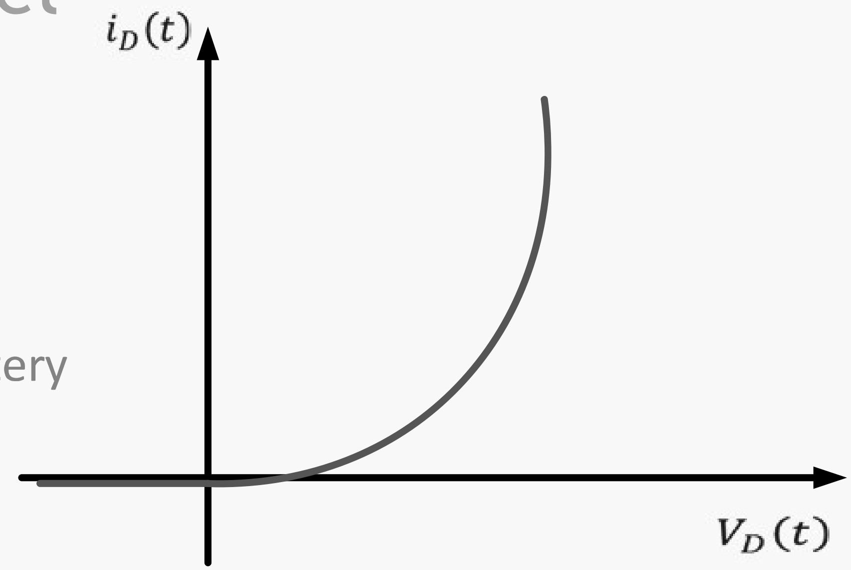




- When $V_S \geq 0$; the Diode is on, and replaced with short circuit
- When $V_S < 0$; the Diode is off, and replaced with open circuit

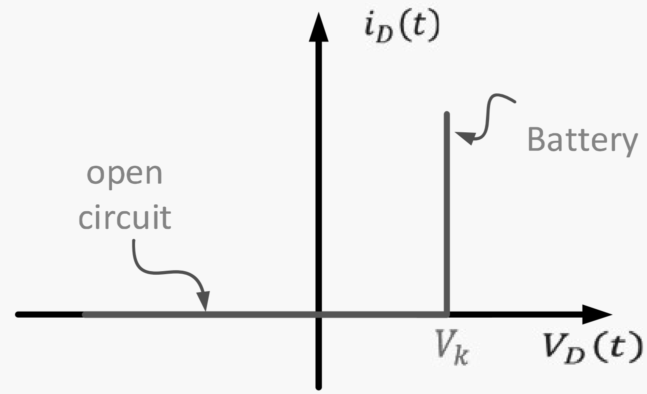
b) Knee Voltage model

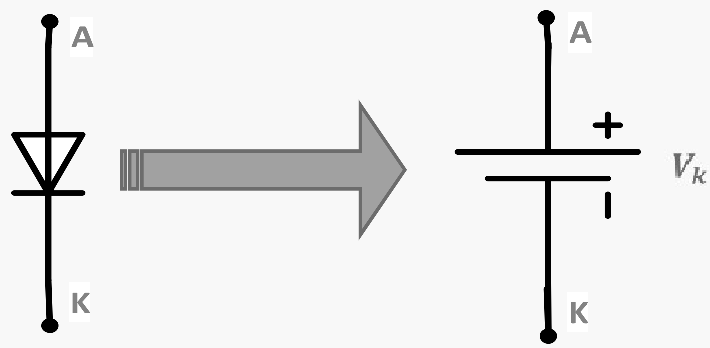




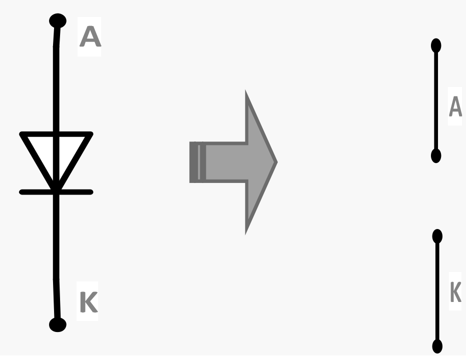
b) Knee Voltage model

- When $V_s \geq V_k$; the Diode is on, and replaced with a constant voltage source

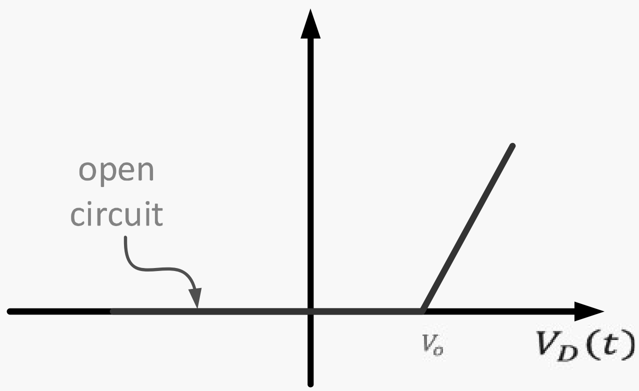


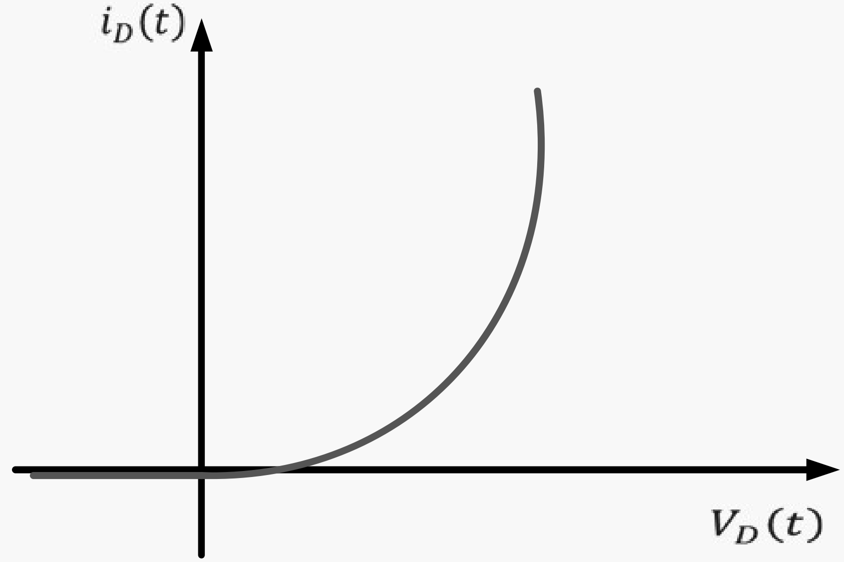


- When $V_s < V_k$; the Diode is off, and replaced with open circuit



c) Dynamic resistance model

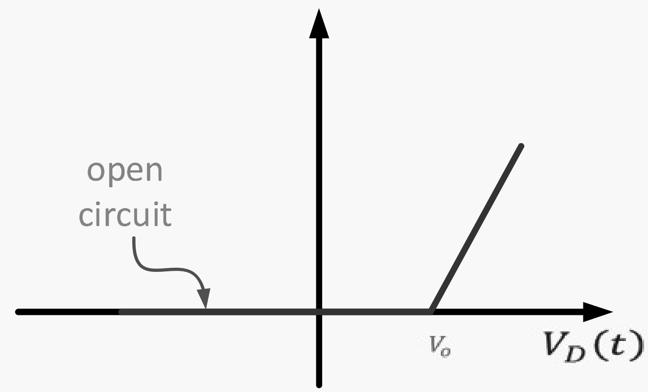


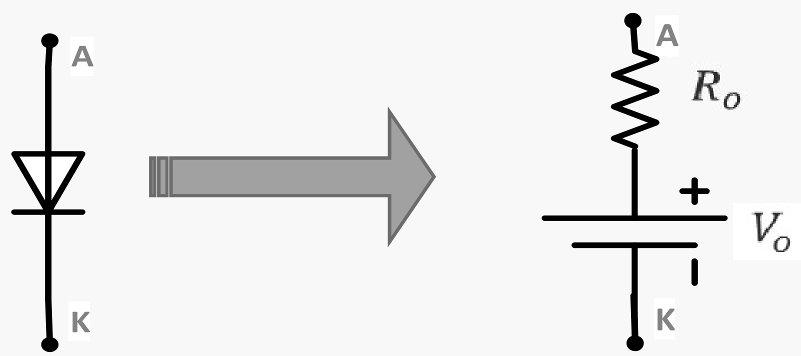


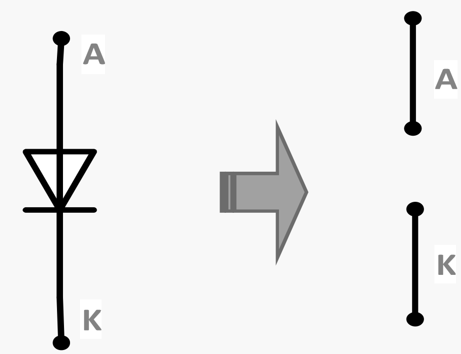
- When $V_S \geq V_o$; the Diode is on, and replaced with a constant voltage source V_o and resistance R_o
- When $V_S < V_o$; the Diode is off, and replaced with open circuit

c) Dynamic resistance model

- When $V_S \geq V_o$; the Diode is on, and replaced with a constant voltage source V_o and resistance R_o



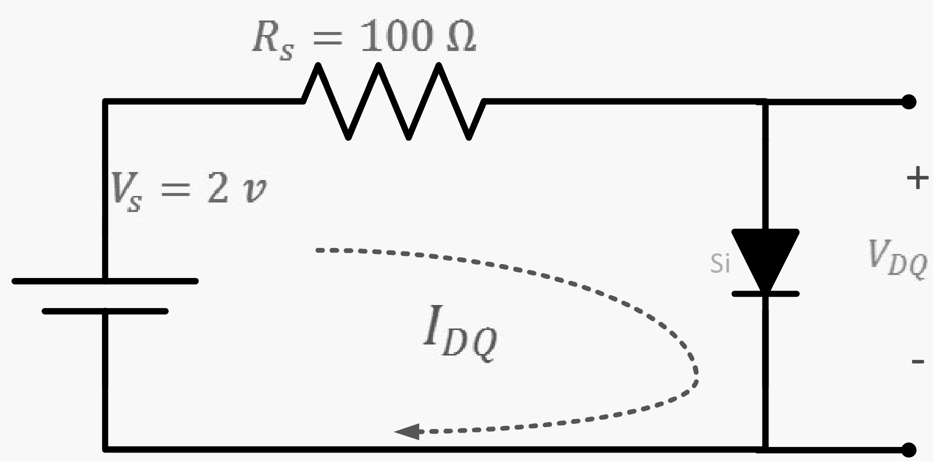




- When $V_S < V_o$; the Diode is off, and replaced with open circuit

Example

- Find the Q point (I_{DQ} , V_{DQ}) using
  - a) ideal diode model
  - b) knee voltage model

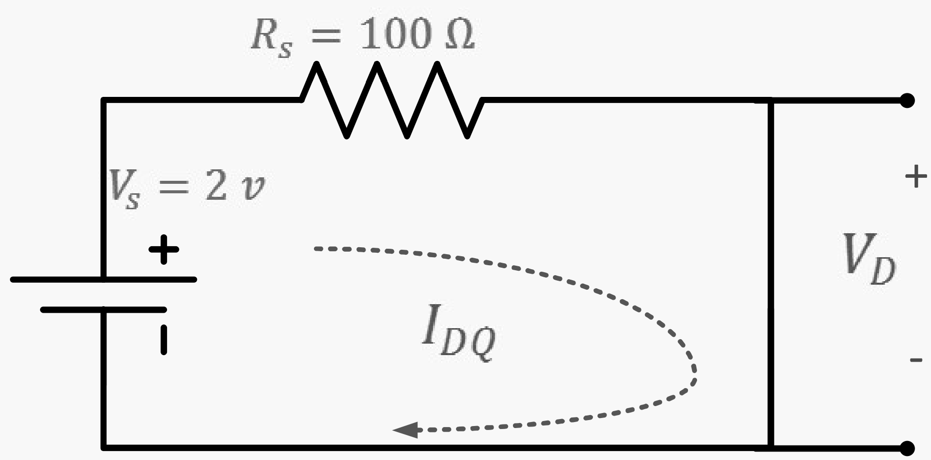


a) using ideal diode model

since $V_S \geq 0$, the diode is on and replaced with short circuit .

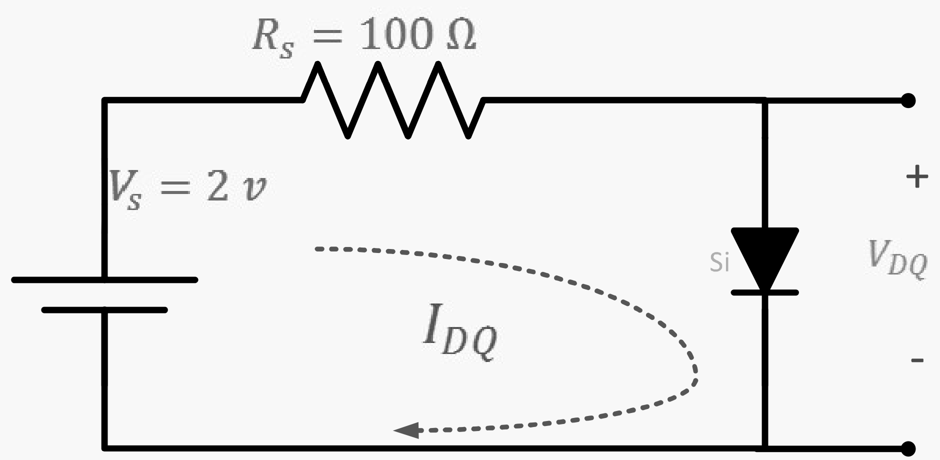
$\therefore \ I_{DQ} = \frac{2}{100} = 20\,mA$

$\therefore \ V_{DQ} = 0\,V$

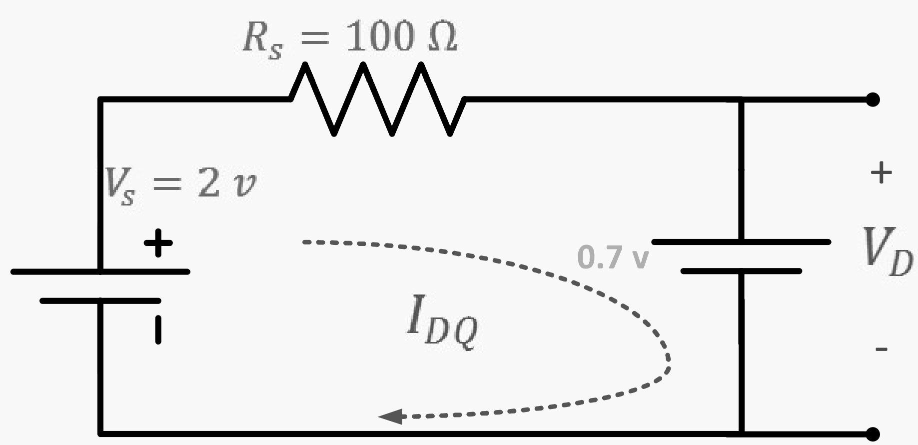


b) Using knee voltage model

since $V_S \geq 0.7$, the diode is on and replaced with $V_k = 0.7$.



$$\therefore\ I_{DQ} = \frac{2-0.7}{100} = 13\ mA$$



$$\therefore\ V_{DQ} = 0.7\ V$$

c) using nonlinear mathematic

$$I_{DQ} = 12.137\, mA$$

$$V_{DQ} = 0.7863\, V$$

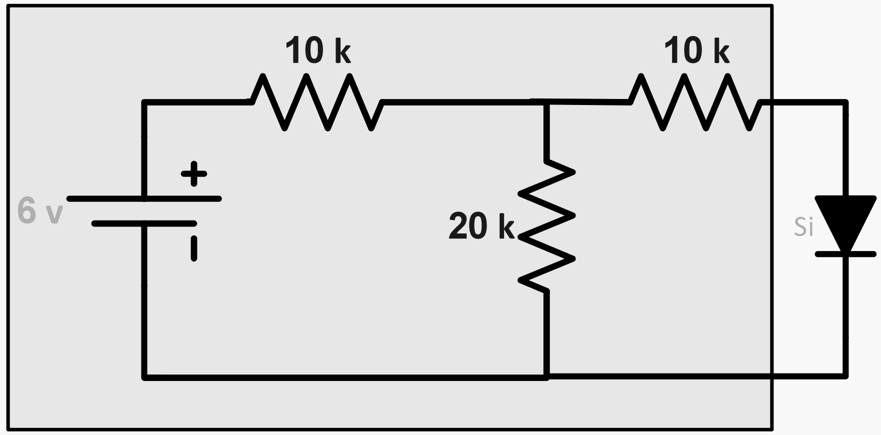
Taking the knee voltage into a count

- If $V_S > 10\,V_k$, we could use ideal diode model .
- If $V_S < 10\,V_k$, we must use knee voltage model .

Diode large signal application

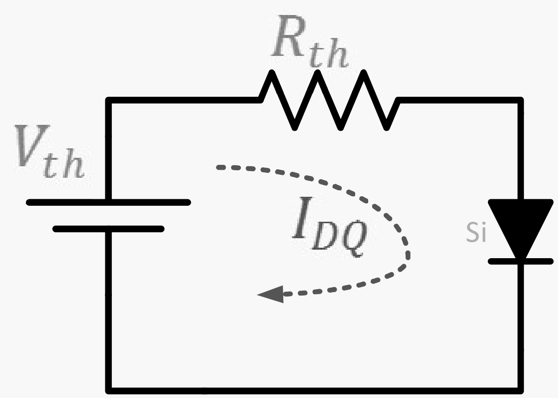
Example

- Find the Q point



Using thevenin's theorem , the circuit is simplified to

$R_{th} = 10k + 10k \,||\, 20k = 16.7k$

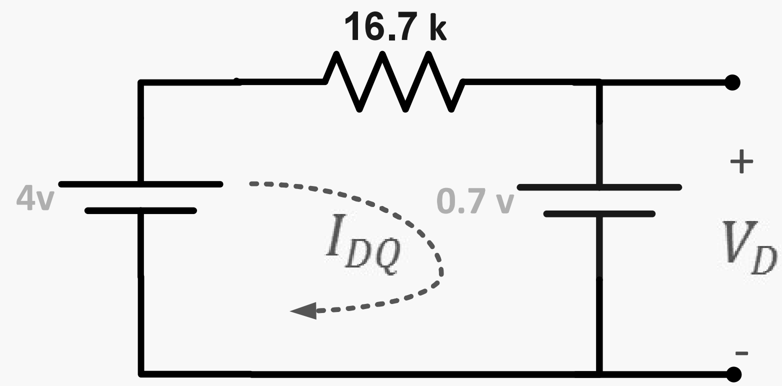


$V_{th} = \frac{20k}{20k+10k} * 6 = 4\,V$

since $V_{th} \geq V_k$, the diode is on

since $V_{th} < 10\,V_k$, we must use the knee voltage model

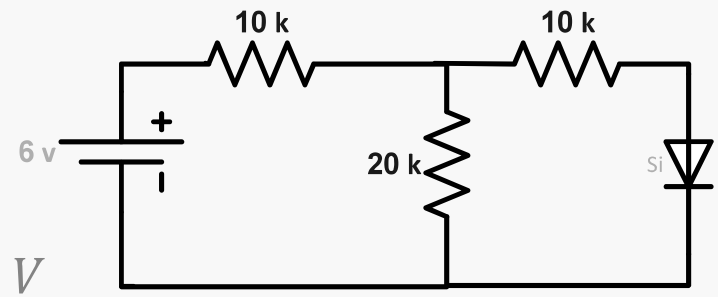
Knee voltage model



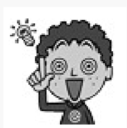
$$I_{DQ} = \frac{4 - 0.7}{16.7K} = 0.198\, mA$$

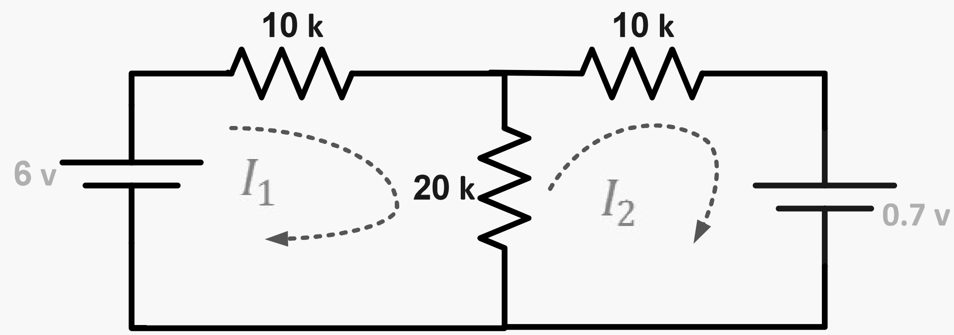
$$V_{DQ} = V_K = 0.7\, V$$

Second method



assume the diode is on , replace it with $V_K = 0.7\ V$





KVL:

$$6 = 30\,I_1 - 20\,I_2$$

$$-0.7 = -20\,I_1 + 30\,I_2$$

Solve for:

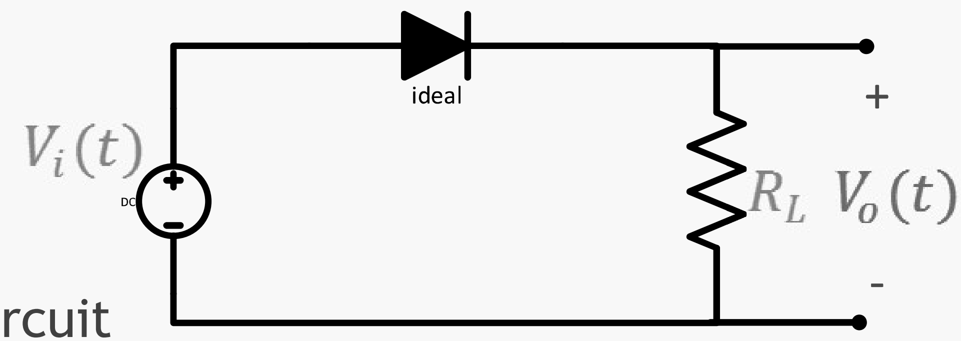
$$I_2 = 0.198\ mA$$

$$\therefore\ I_D = I_2 = 0.198\ mA$$

Since $I_D > 0$, $\therefore$ our assumption is ok

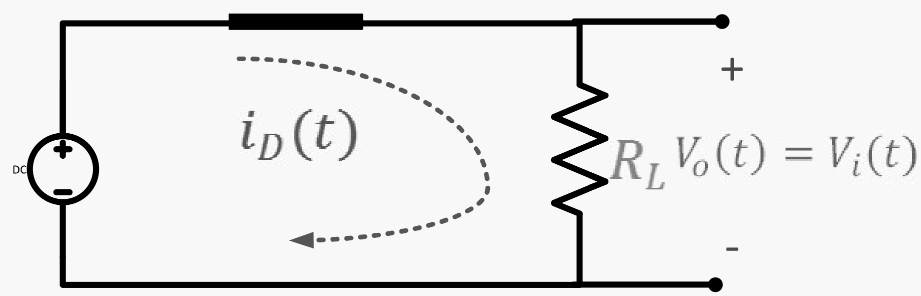
Diode large – signal application

1) Diode clipper circuit



a) assume the diode is on

replace it with short circuit



$i_D(t) > 0$

$i_D(t) = \frac{V_i(t)}{R_L} > 0$

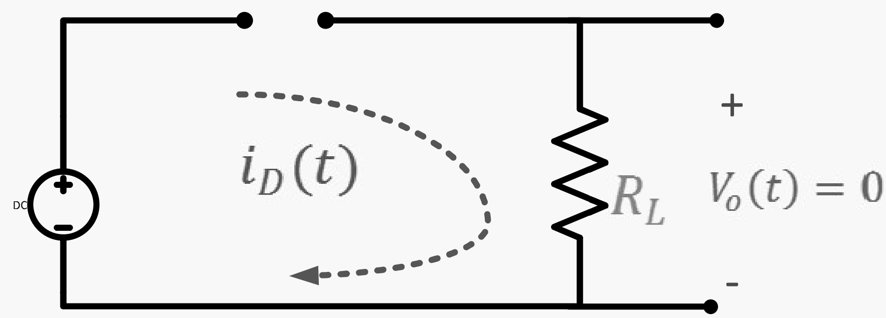
$\therefore V_i(t) > 0$

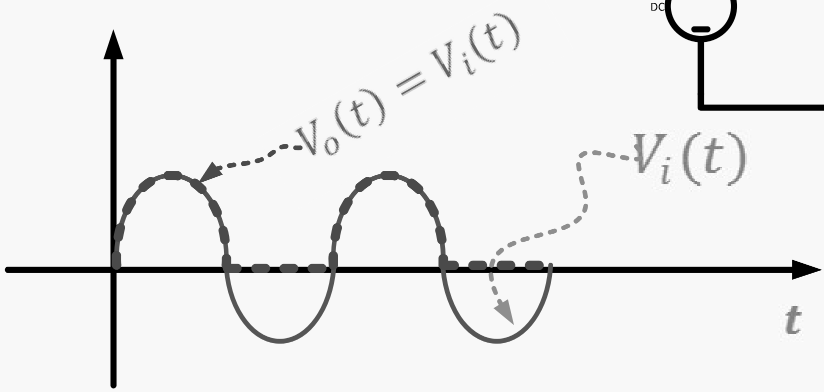
$\therefore$ when $V_i(t) > 0$, the diode is on and

$V_O(t) = V_i(t)$

∴ when $V_i(t) < 0$, the diode is off and $V_O(t) = 0$.

$V_O(t) = 0$.





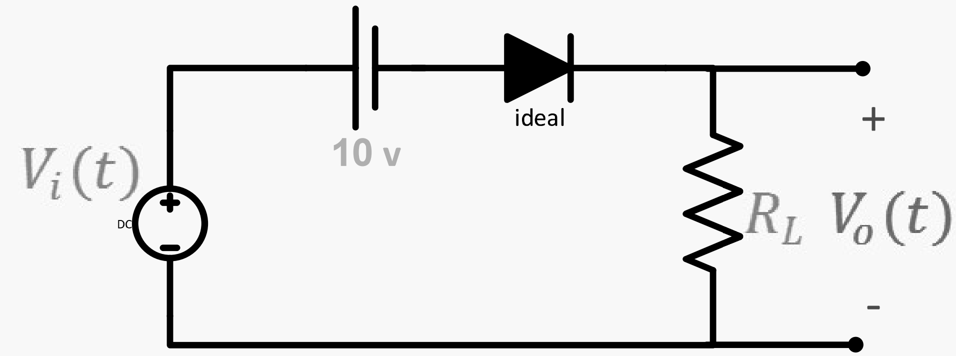
∴ the clipper circuit used to eliminate portion of the input signal .

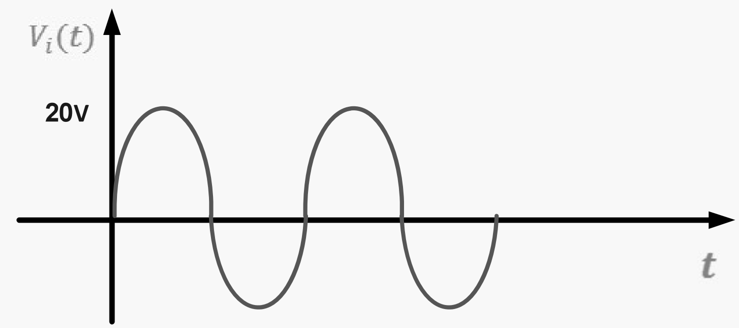
Example

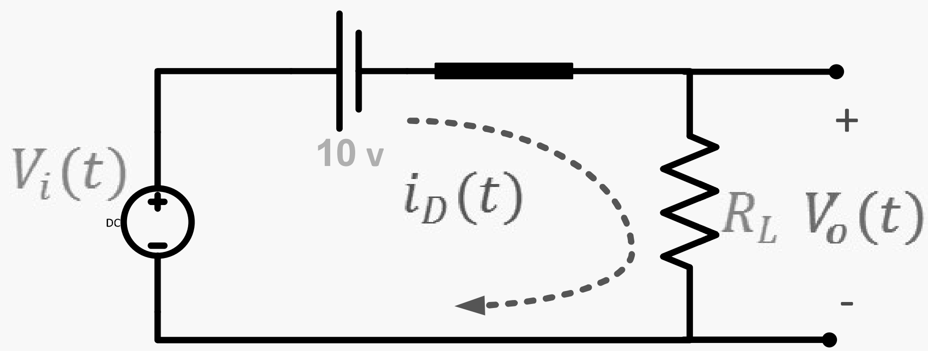
a) assume that the diode is on

b) replace it with short circuit

c) $i_D(t) > 0$

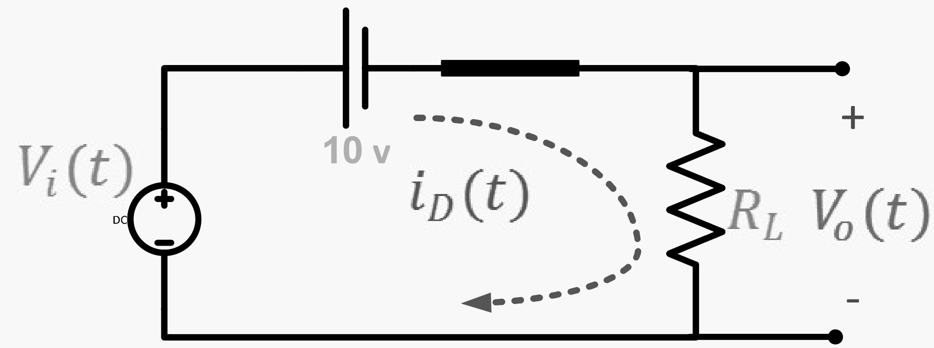






$$i_D(t) = \frac{V_i(t) - 10}{R_L} > 0$$

$$i_D(t) = \frac{V_i(t) - 10}{R_L} > 0$$



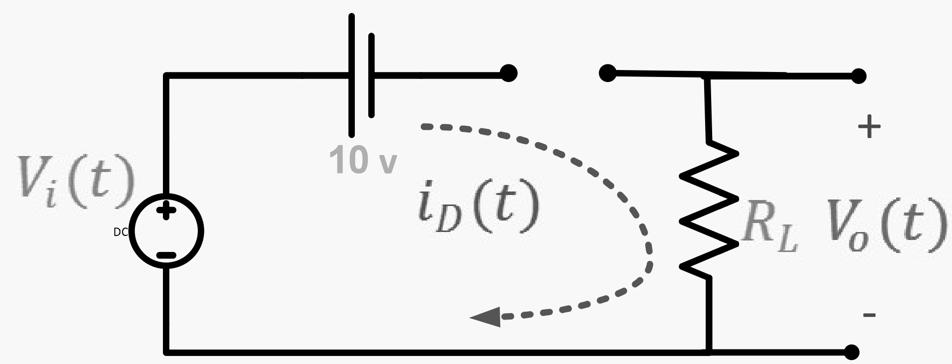
$\therefore\ V_i(t) - 10 > 0$

$\therefore\ V_i(t) > 10$

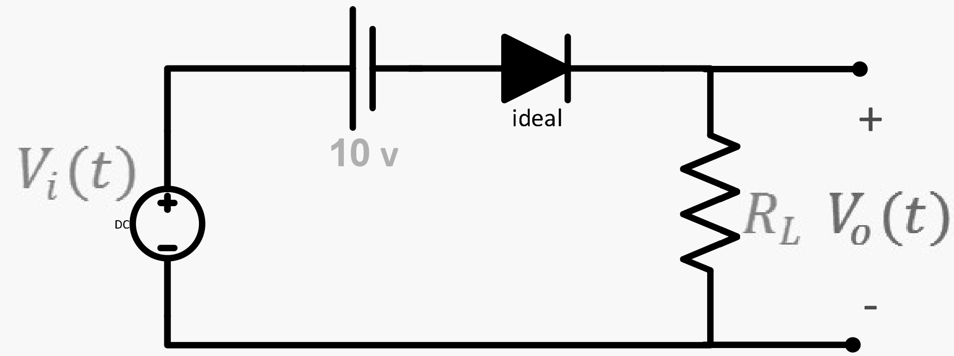
$\therefore$ when $V_i(t) > 10$ V , the diode is on and
$V_O(t) = V_i - 10$

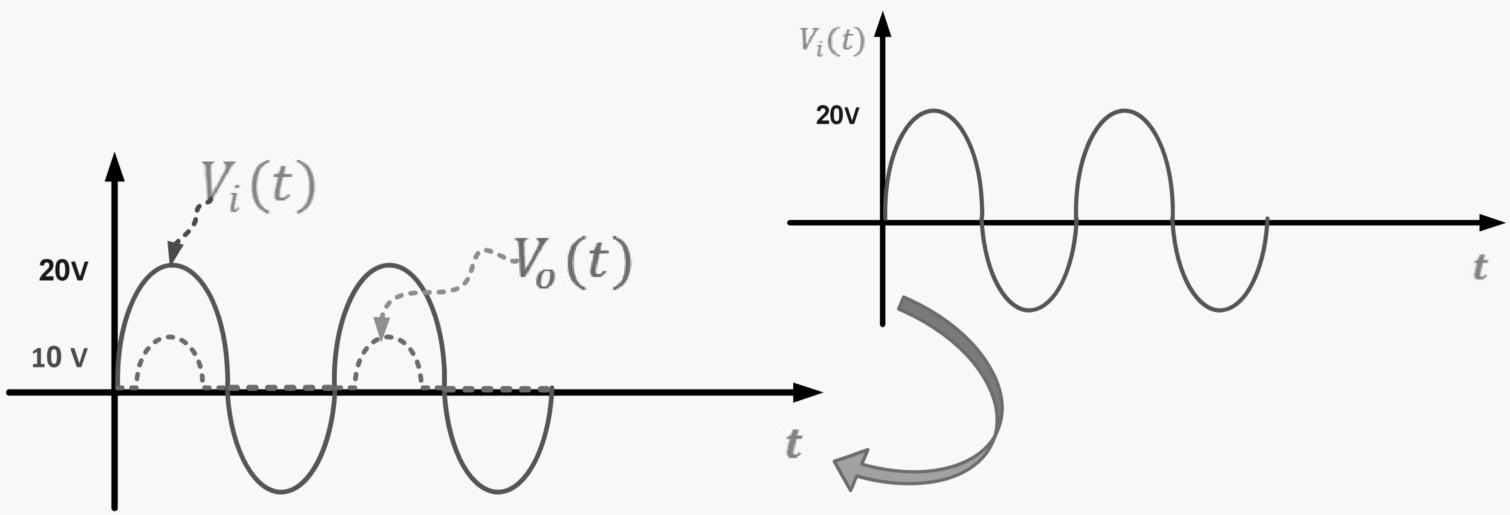
and also we can prove that when $V_i(t) < 10\,V$, the diode is off

$\therefore\ V_O(t) = 0$



The output





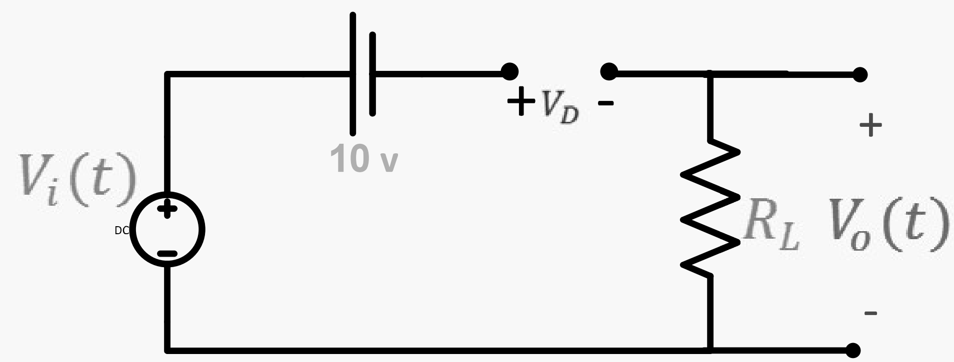
Second method

a) assume that the diode is off , b) replace it with open circuit , c) $V_D(t) < 0$.

$V_D(t) < 0$

$V_D(t) = -10 + V_i$

$V_i(t) < 10$ V



∴ when $V_i(t) < 10$ V , the diode is off and $V_O(t) = 0$

Diode-Large-Signal-Applications Diode

Clipping at two independent levels

Clamping Circuits

Voltage Multipliers

Clipping at two independent levels

D_1 , D_2 are ideal

1) Assume D_1 on, and D_2 off

$V_o(t) = 5\ v$

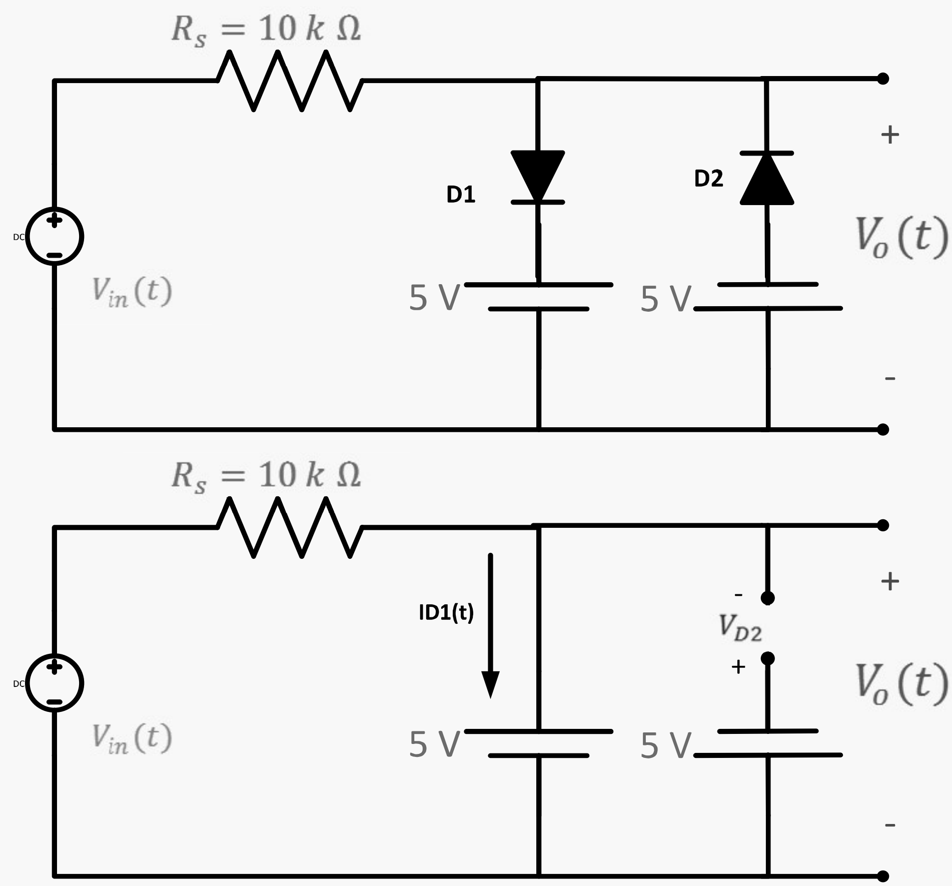
$i_{D1}(t) = \frac{V_i(t) - 5}{10k} > 0$

$\therefore V_i(t) - 5 > 0$

$\therefore V_i(t) > 5\ v$

$V_{D2}\,(t) = -5 - 5 = -10\ v$

$\therefore$ When $V_i(t) > 5\ v$, $V_o(t) = 5\ v$



- 2) Assume D_2 on, and D_1 off

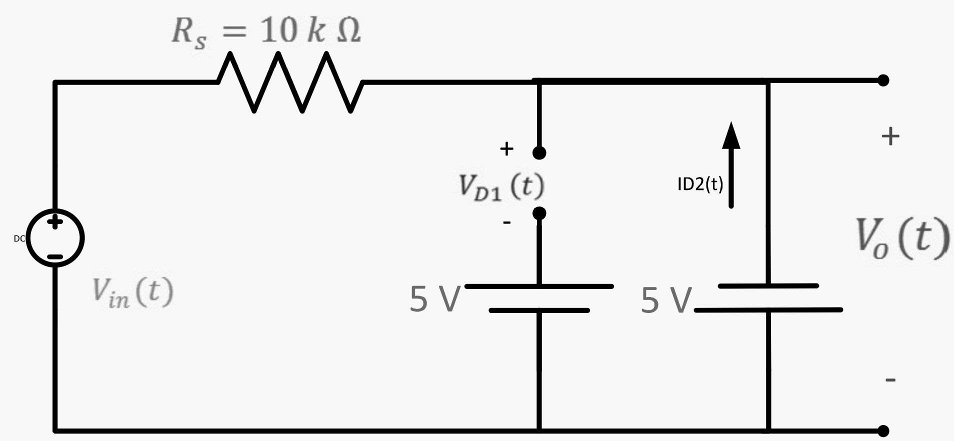
$V_o(t) = -5\ v$

$i_{D2}(t) = \frac{-V_i(t) - 5}{10k} > 0$

$-V_i(t) - 5 > 0$

$\therefore\ V_i(t) < -5\ v$

$V_{D1}(t) = -5 - 5 = -10\ v$

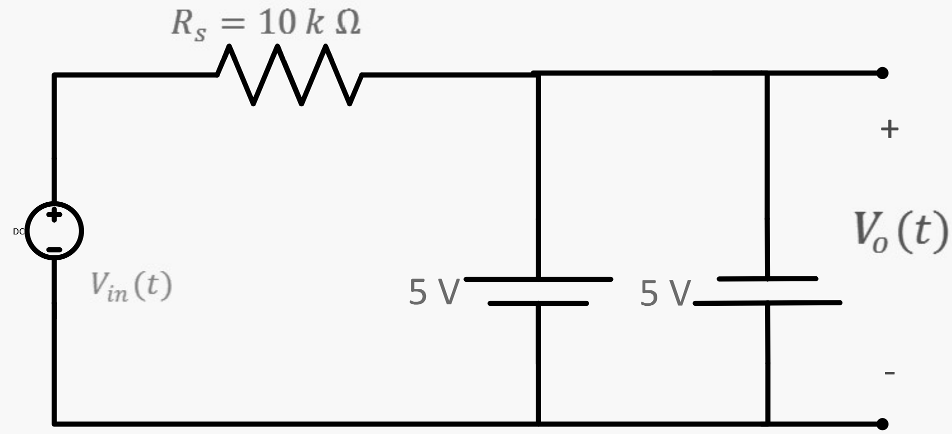


$\therefore$ When $V_i < -5v$, $V_o(\text{t}) = -5v$

- 3) Assume that D_1 and D_2 are on

$V_o = -5\ v$

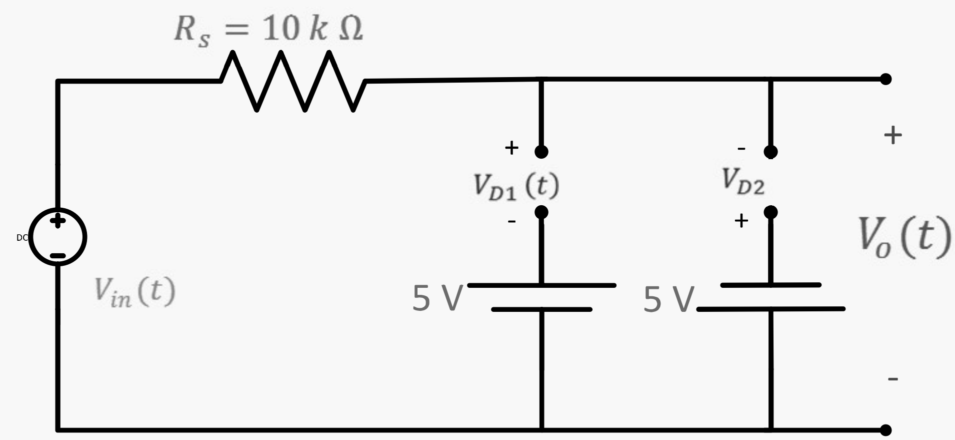
also V_o = +5 ??



This case is not valid

Impossible

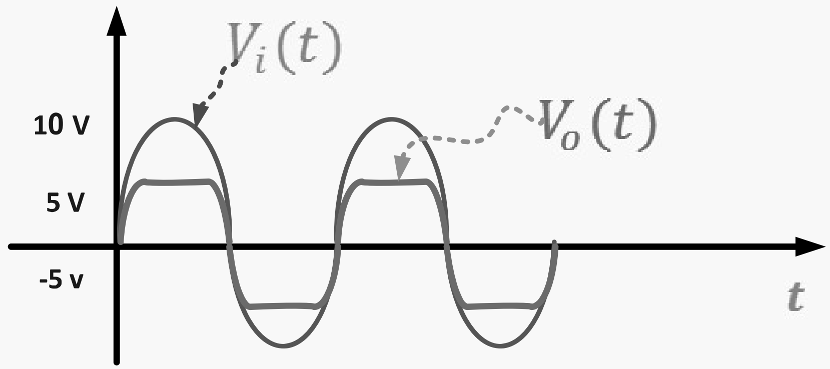
- 4) Assume that D_1 , and D_2 are off



- When +5 > $V_i(t)$ > -5

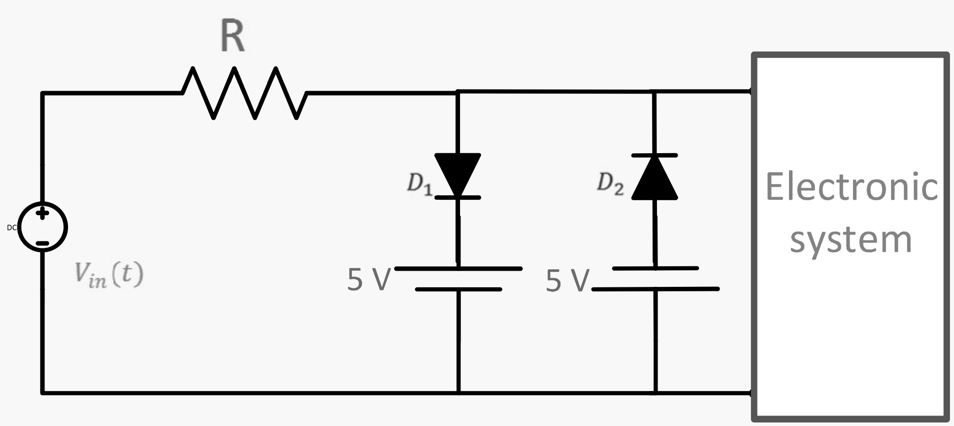
$V_o(t)$ = $V_i(t)$

Clipping at two independent levels

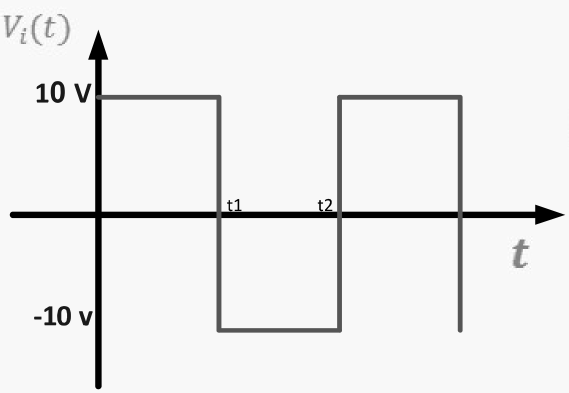


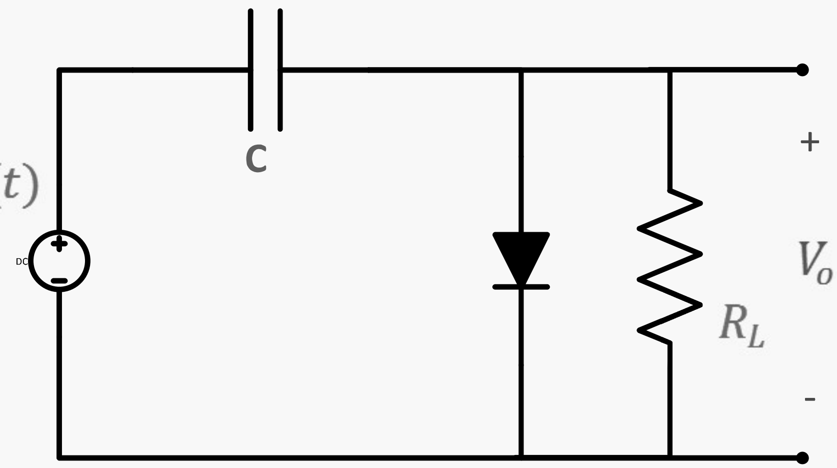
Limiter

For protection



2) Clamping circuit





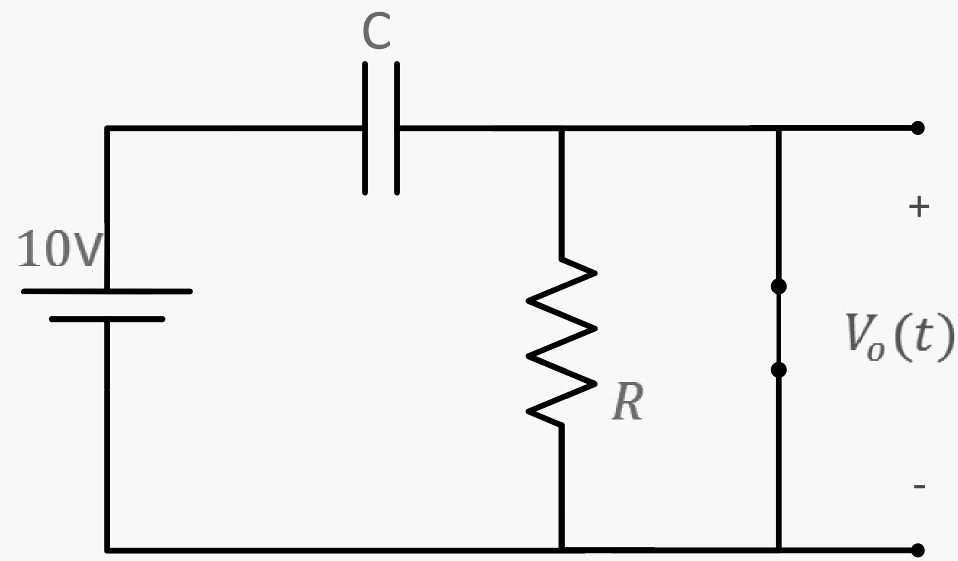
- Diode is ideal , $V_c(0-) = 0$
- 1) at t= 0^+

$V_i(0^+) = 10v$; $V_c(0^+) = V_c(0^-) = 0$

$\therefore$ $V_D(0^+) = 10v$, $\therefore$ Diode is on and then replaced with short circuit

In the interval $t_1 > t > 0^+$

- $V_i = 10$, Diode is on (short)



$V_0(t) = 0$

and the capacitor charges toward

+10v in 5τ = 5R_{eq}C = 0

In the interval $t_2 > t > t_1$

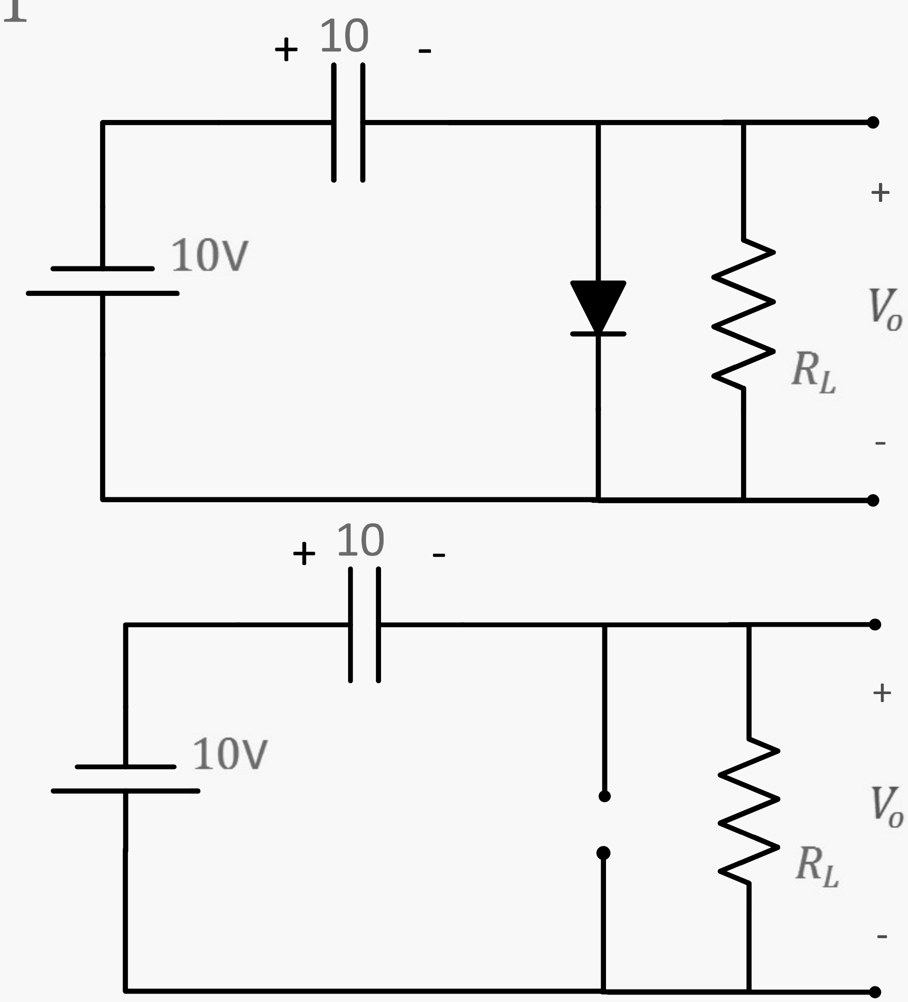
The diode is off and replaced
with open circuit

- $\therefore V_0(t) = -V_c(t) - 10$
- $V_0(t) = -10 - 10$

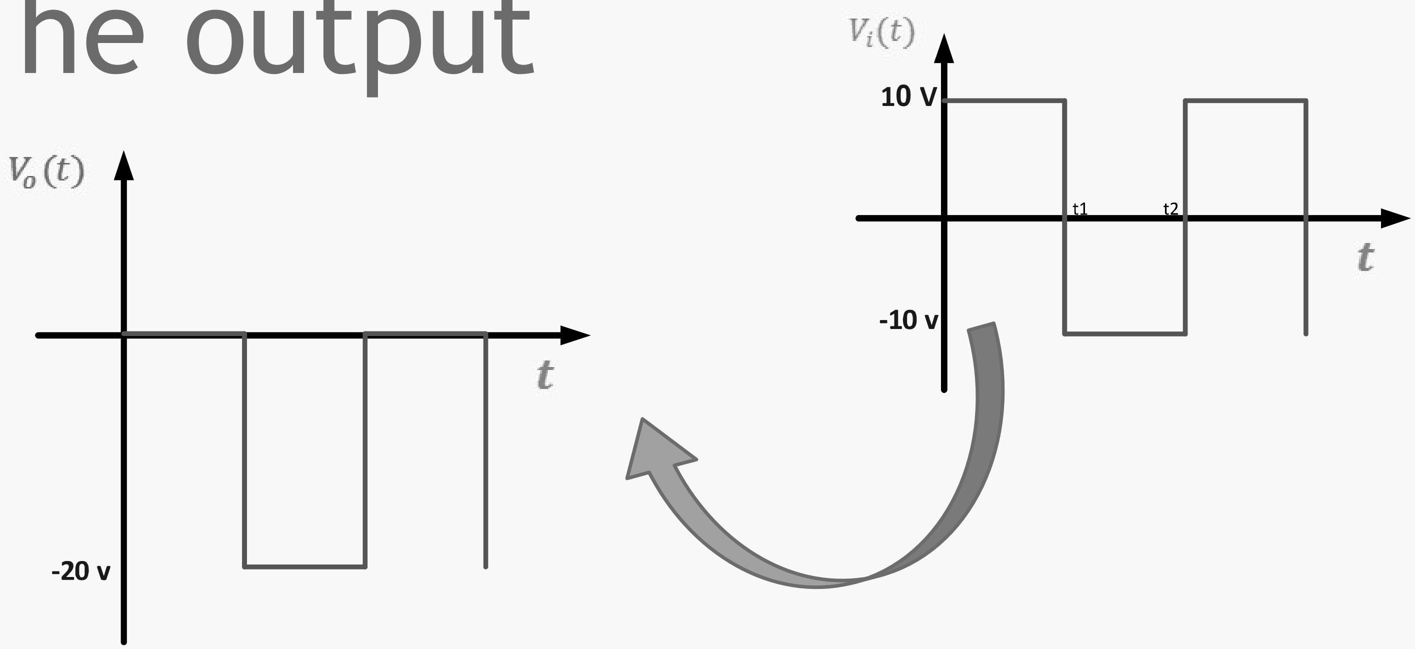
$V_0(t) = -20\ v$

We must choose $RC \gg (t_2 - t_1)$

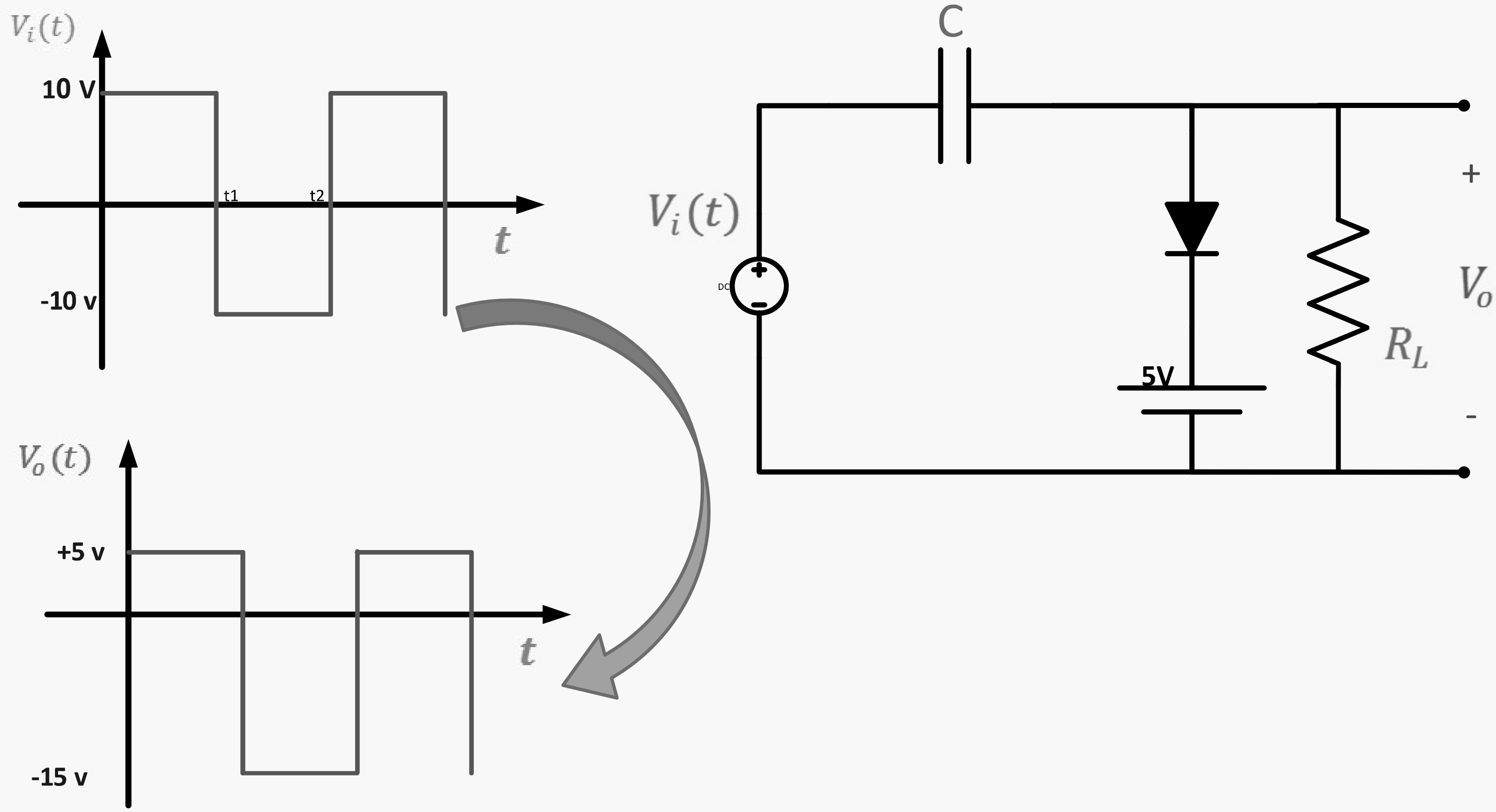
so that $V_c(t) \equiv 10\ v$ in this interval



The output



Biased clamping circuit



3) Voltage Multiplier

D_1 , and D_2 are ideal

$V_{c1}(0^-) = V_{c2}(0^-) = 0$

- A) at t=0^+

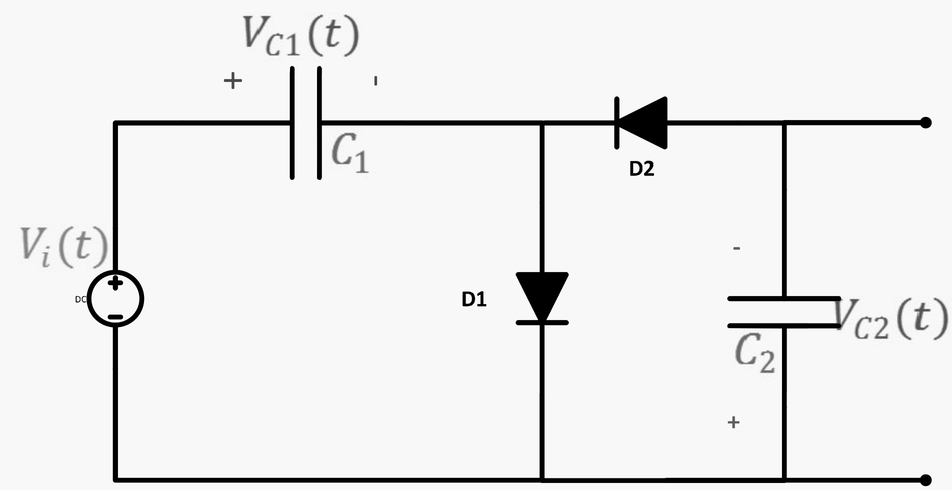
  $V_i(0^+) =$ positive

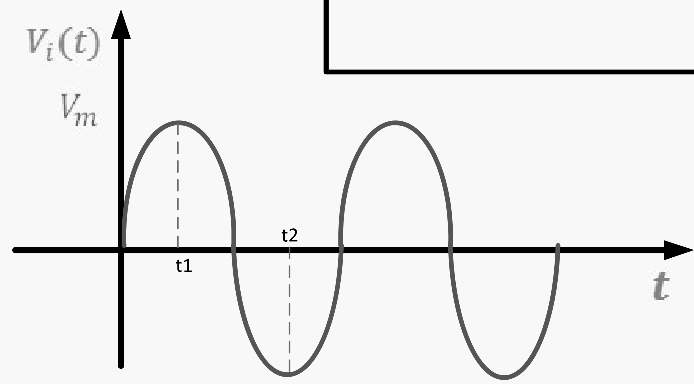
  $V_{c1}(0^+) = V_{c2}(0^+) = 0$

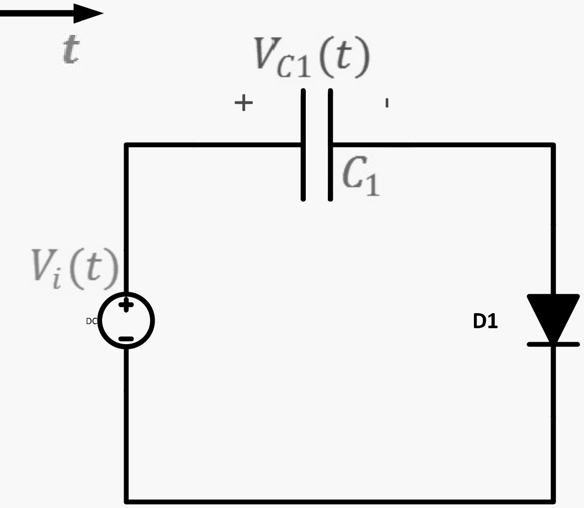
  $\therefore D_1$ on , and D_2 off
- B) in the interval $t1 > t > 0$
- The capacitor

charges towards V_m

at t_1 ; $V_c(t_1) = V_m$







- C) at $t = t_1^+$

  $V_{c1}(t_1^+) = V_m$

  $V_i(t_1^+) < V_m \therefore D_1$ is off , and D_2 is on

- D) in the interval $t_2 > t > t_1$

  C_2 charges toward ?V_m

  at $t = t_2$

  $V_{c2}(t_2) = 2V_m$

  $V_{c2}(t_2) = -V_i(t_2) + V_m$

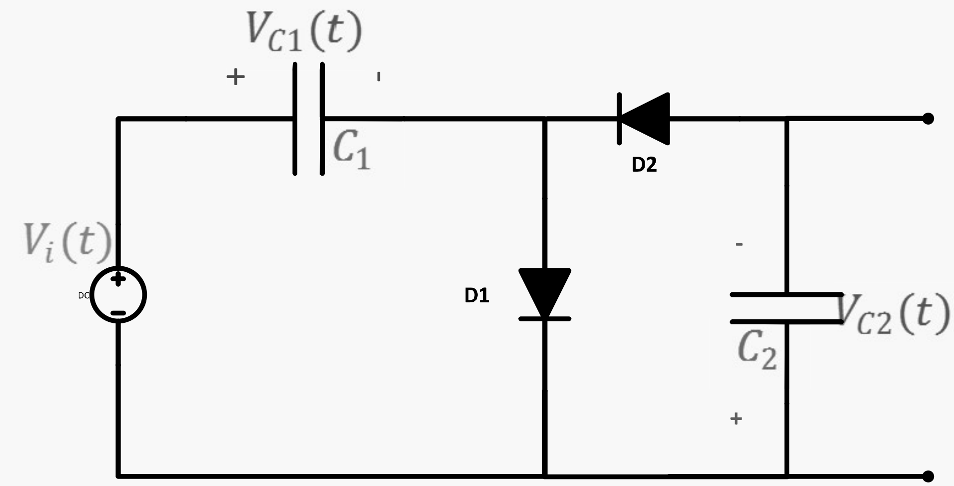
  $V_{c2}(t_2) = V_m + V_m$ $) = 2V_m$

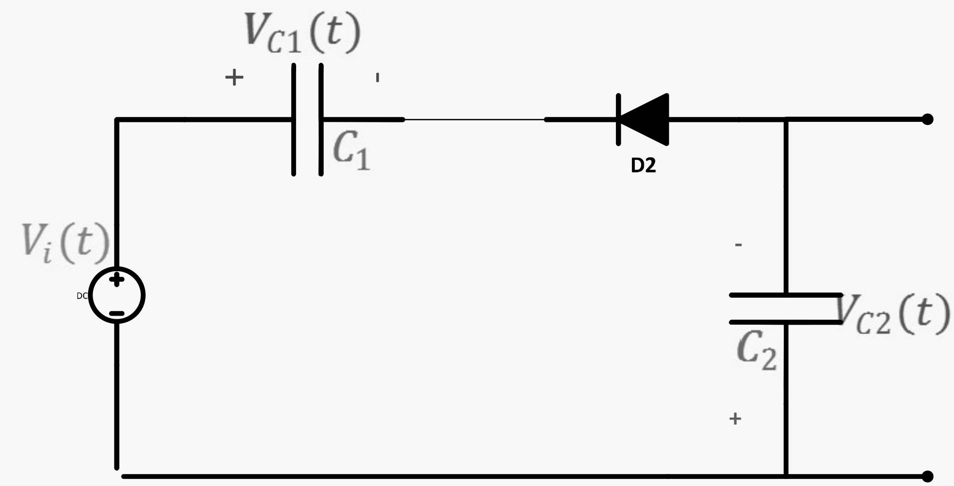
- E) at $t = t_2^+$

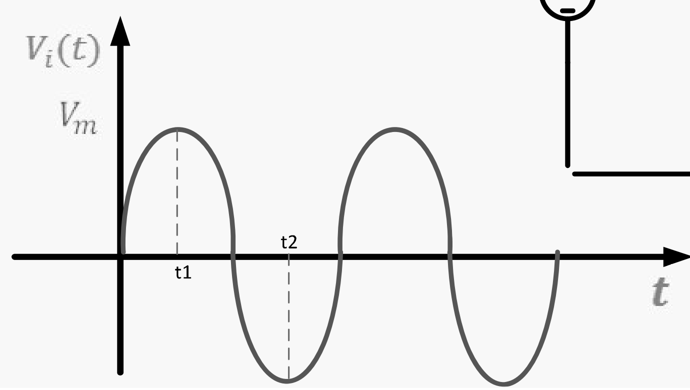
  D_2 is off, D_1 is off

  $V_{c1}(t_2^+) = V_m$

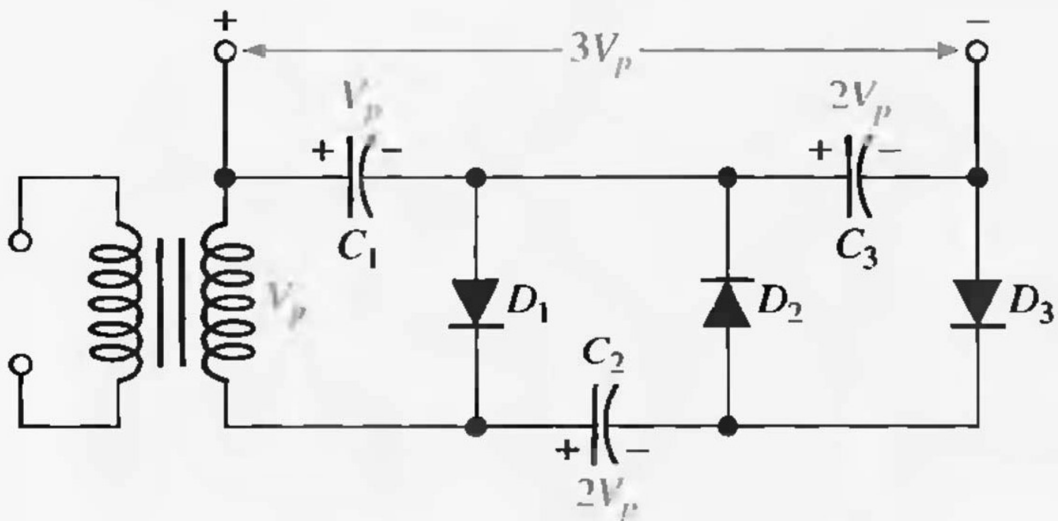
  $V_{c2}(t_2^+) = 2V_m$



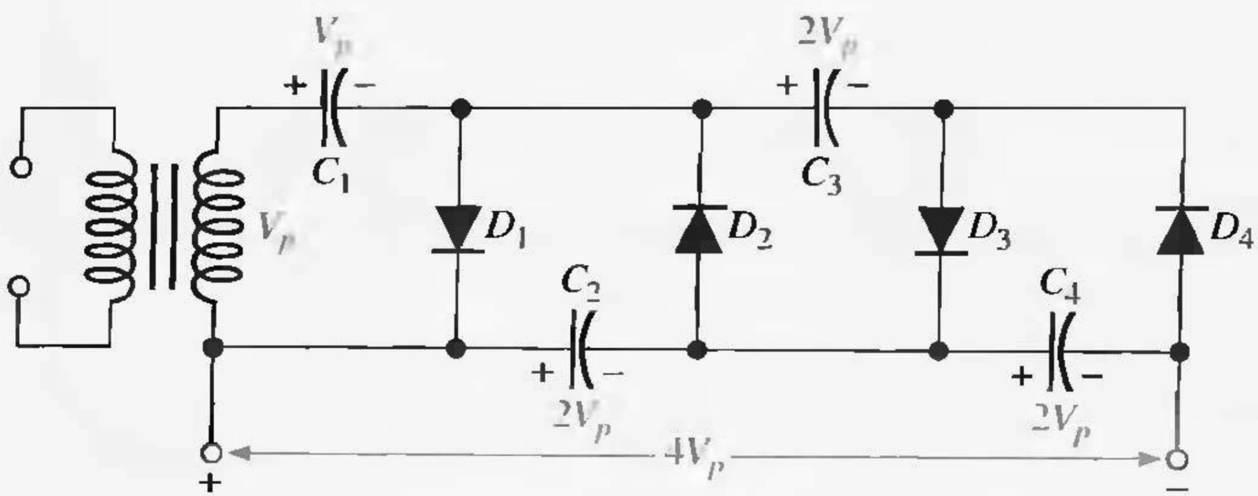




Voltage Tripler



Voltage Quadrupler



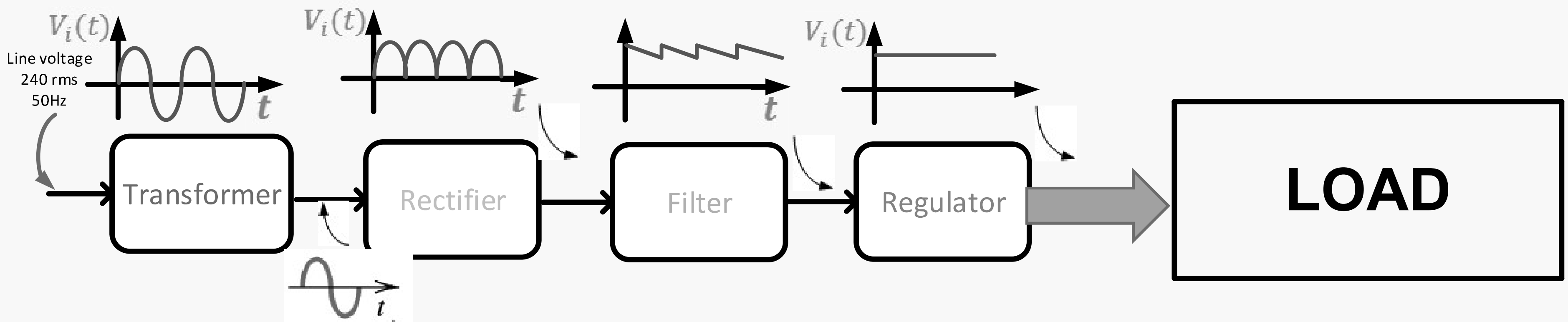
Dc Power Supply

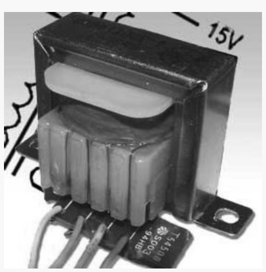
half wave rectifier

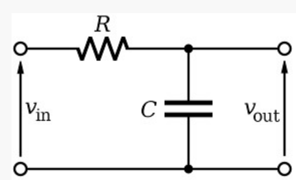
center tapped transformer

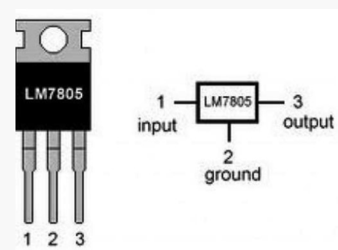
Dc Power Supply

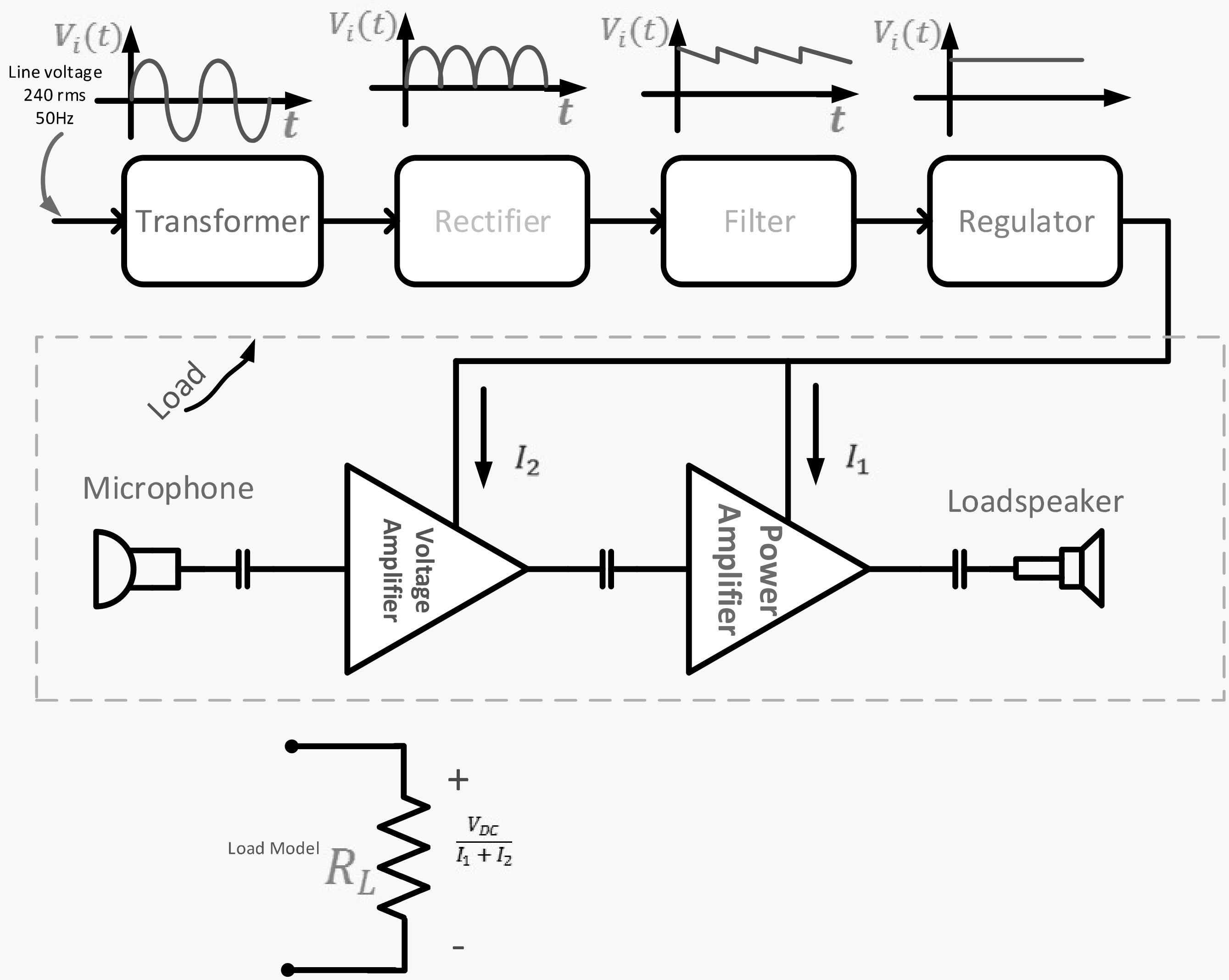
- All electronic circuits and systems require a stable source of dc voltage and current (or dc power) to operate correctly.









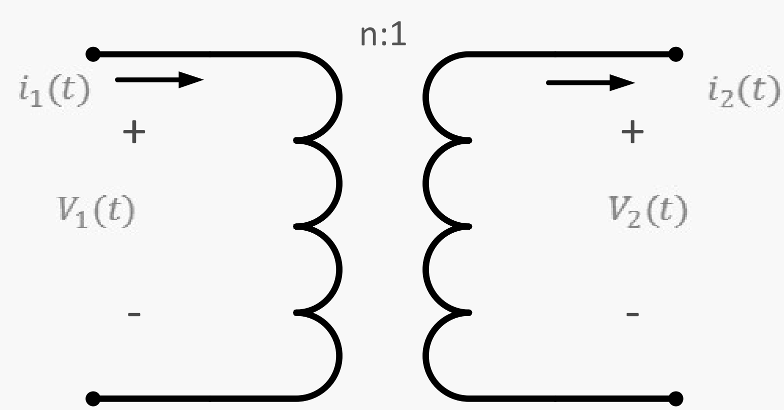


Line voltage
240 rms
50Hz
$V_i(t)$
t
Transformer
Rectifier
Filter
Regulator
Load
I_2
I_1
Microphone
Voltage Amplifier
Power Amplifier
Loadspeaker
Load Model
R_L
+
-
$\frac{V_{DC}}{I_1 + I_2}$

Dc Power Supply

- The basic power supply consists of a transformer, rectifier, filter, and a regulator.
- Transformer: Used to increase or decrease the amplitude of the line voltage
- $$\boldsymbol{V_2(t) = \frac{1}{n}\, V_1}$$

  $$i_2(t) = n\, i_1(t)$$



Dc Power Supply

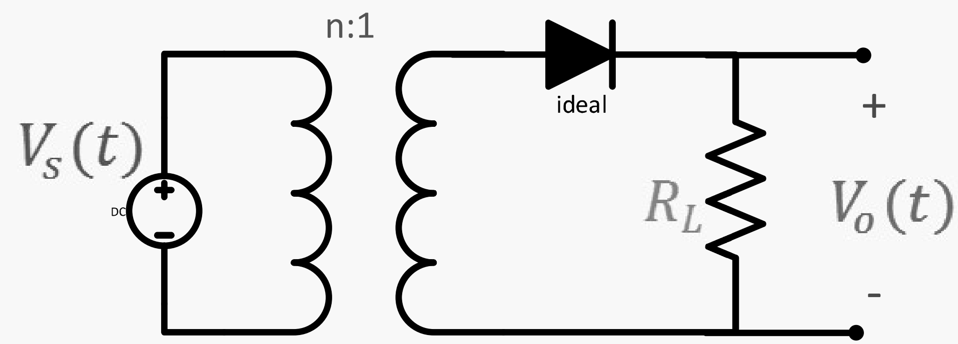
- Rectifier: **used to convert the ac voltage (zero- average value) into either positive and negative pulsating dc.**
- 1) Have- Wave Rectifier
- $V_i(t) = \frac{V_s(t)}{n}$
- **A)** **when $V_i(t) > 0$, Diode is on (short circuit)**

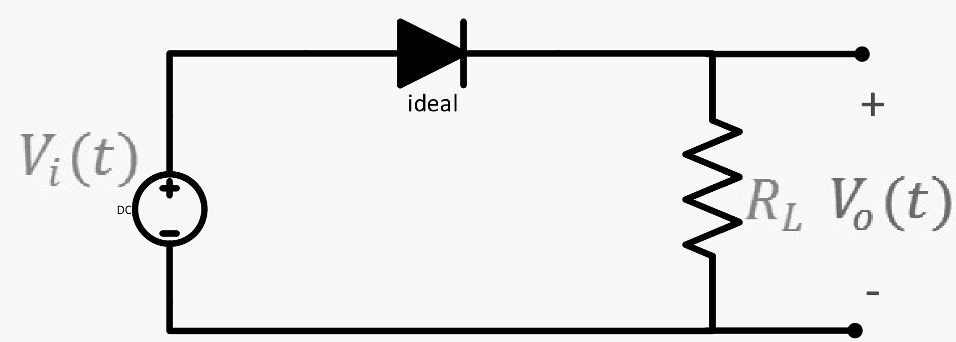
  $\therefore V_o(t) = V_i(t)$

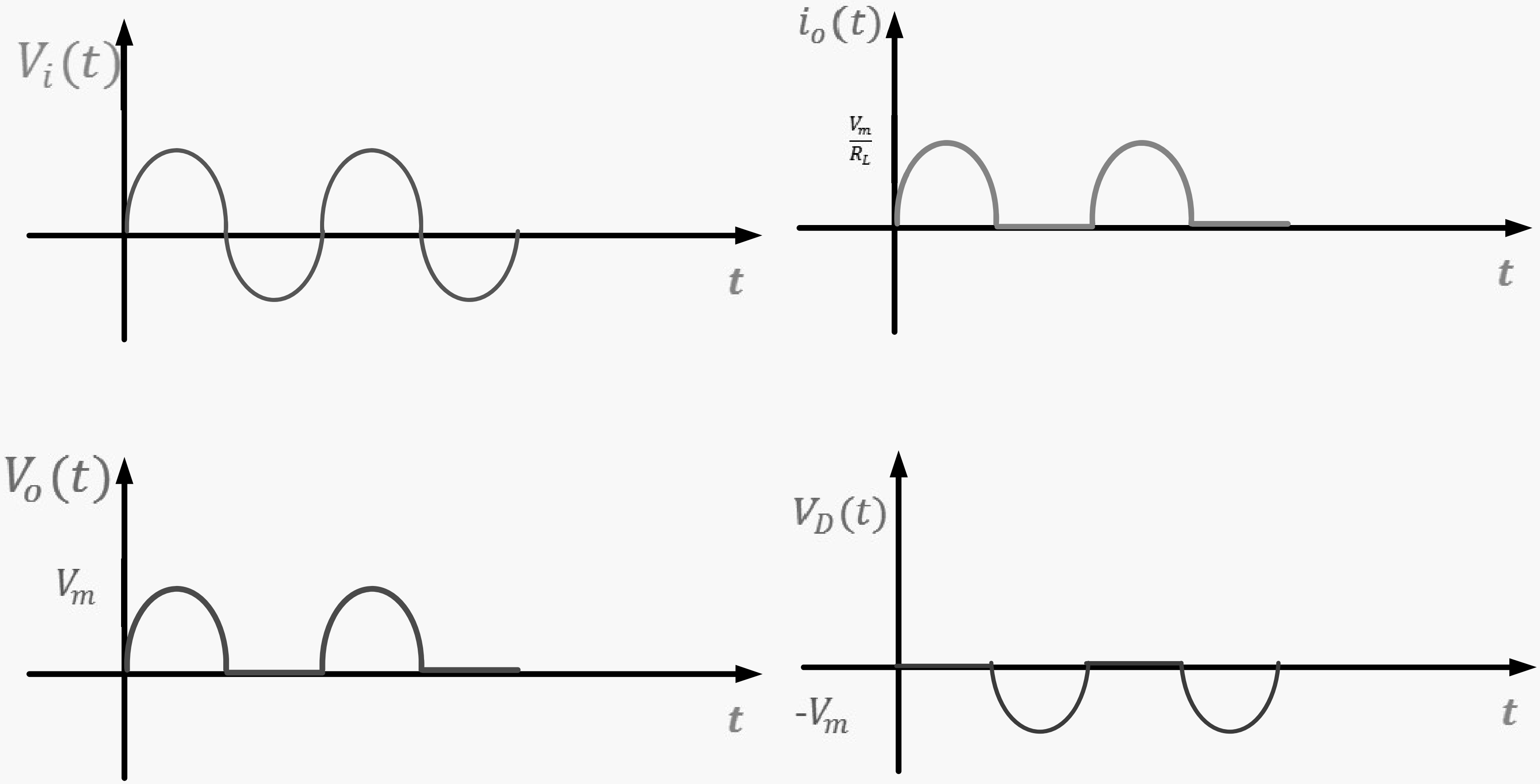
  $\therefore V_D(t) = 0$
- **B)** **when $V_i(t) < 0$, Diode is off (open circuit)**

  $\therefore V_o(t) = 0$

  $\therefore V_D(t) = V_i(t)$





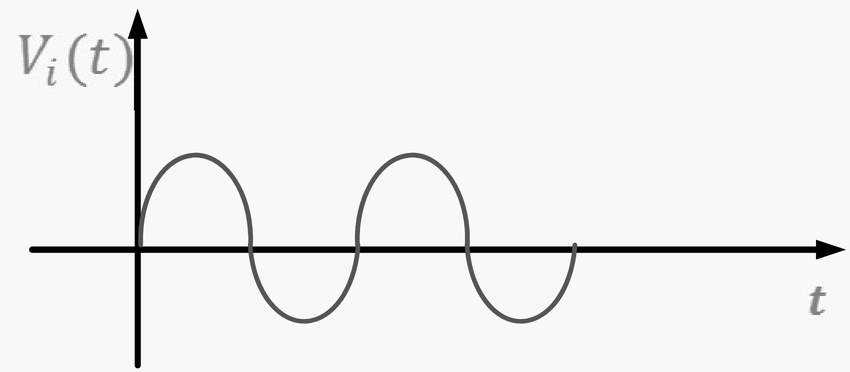


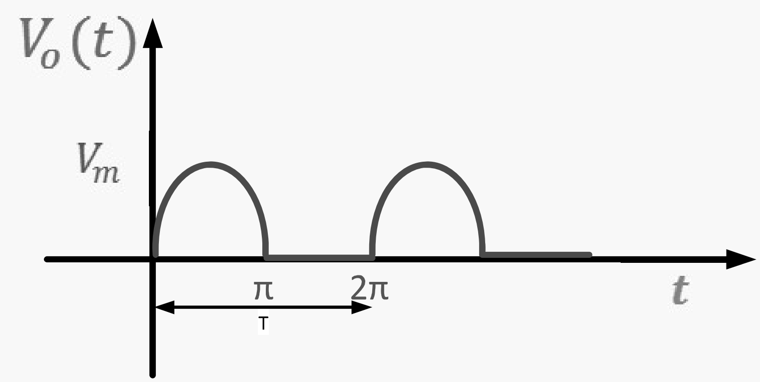
$V_i(t)$
t
$i_o(t)$
$\frac{V_m}{R_L}$
t
$V_o(t)$
V_m
t
$V_D(t)$
$-V_m$
t

- $V_{o,av} = \frac{1}{T} \int_0^T V_o(t)dt$

  $= \frac{1}{2\pi} \int_0^{\pi} \sin\theta \; d\,\theta$

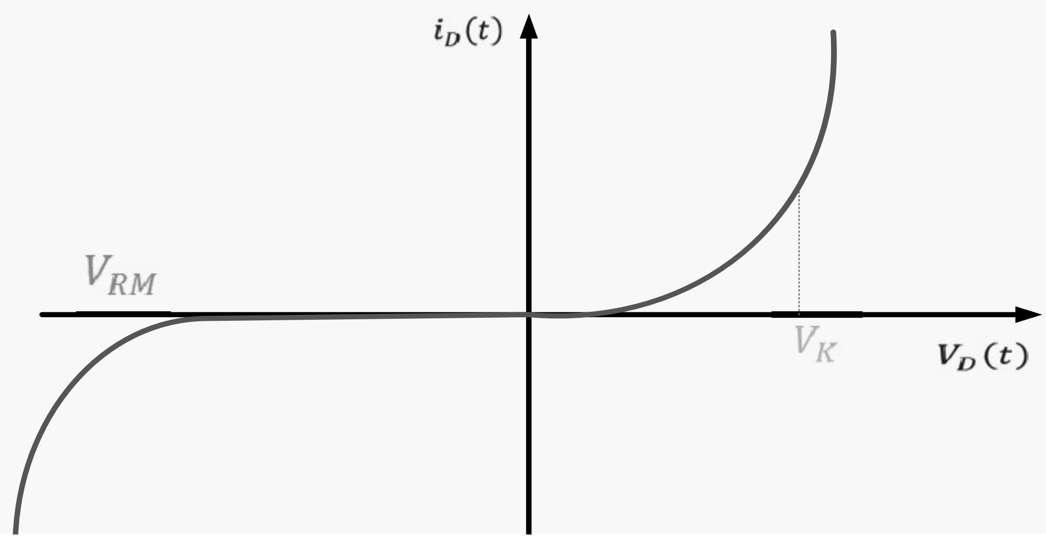
- $V_{o,av} = \frac{V_m}{\pi}$
- $\mathrm{T} = T_o$
- $f = f_o$
- $i_{D(t),av} = \frac{V_m}{\pi R_L}$





Important Electrical Ratings

- I_{FM} = maximum forward current
- I_{FM} = maximum average current that can safely be sustained by the diode when it is forward biased
- V_{RM} = maximum reverse voltage
- V_{RM} = maximum voltage that can be applied to the diode in the reverse bias polarity before voltage break down occur
- PIV ≡ Peak Inverse Voltage
- PIV = V_{RM}



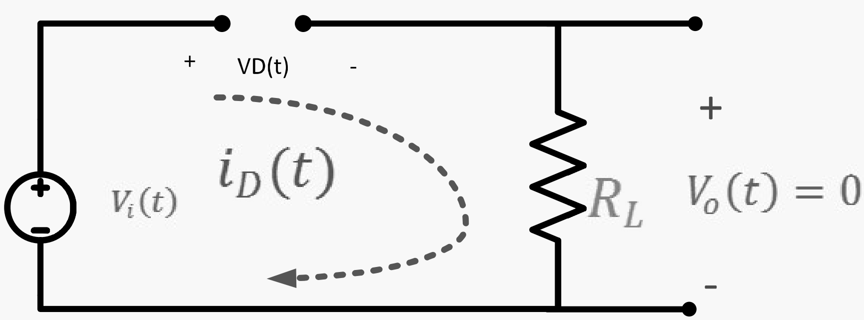
- ∴ For the have-wave rectifier

$$V_{o,av} = \frac{V_m}{\pi}$$

$$I_{FM} = \frac{V_m}{\pi R_L}$$

$$\text{PIV} = -V_m$$

- When $V_i(t) < 0$, Diode is off



- $V_D(t) = V_i(t) < 0$

$$V_D(t)_{,max} = -V_m$$

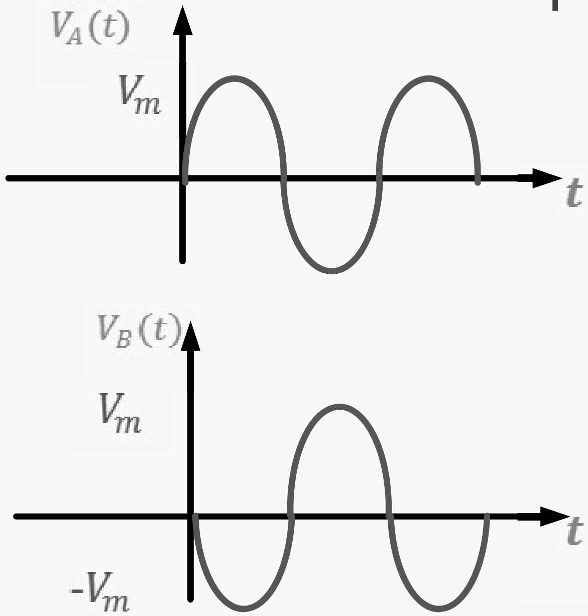
Full-Wave Rectifier

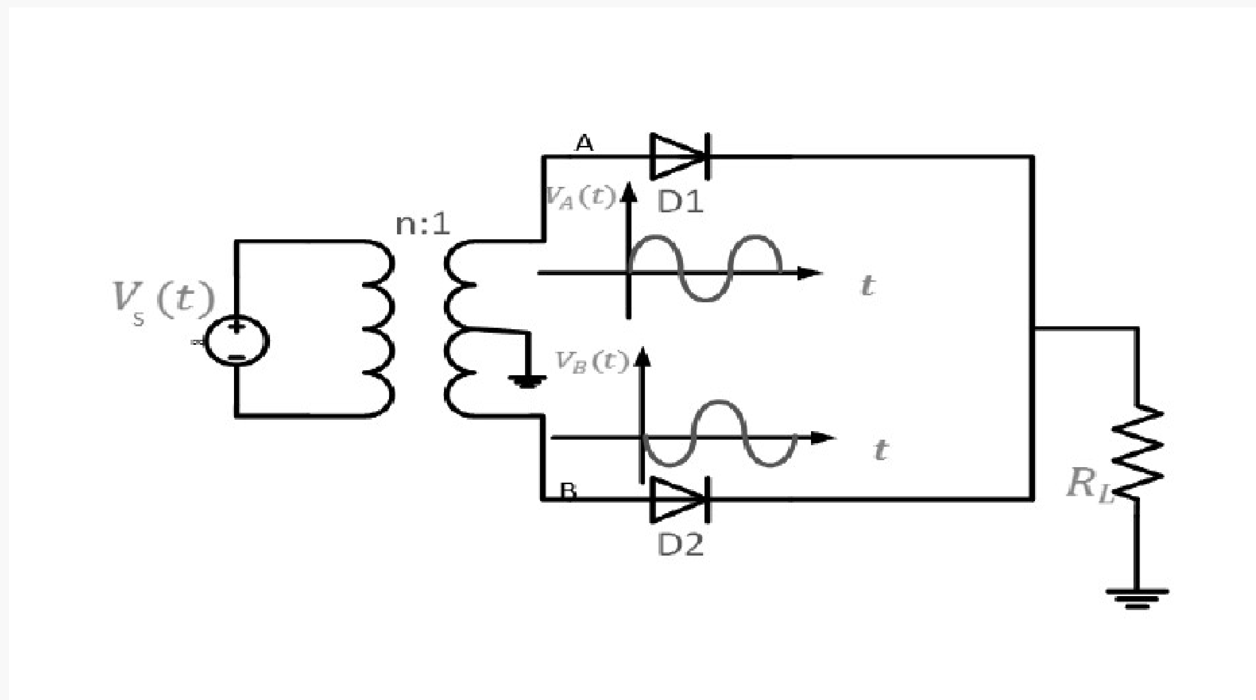
$$V_A(t) = -\ V_B(t)$$

$$V_A(t) = \frac{1}{n}\ V_s(t)$$

$$V_B(t) = -\frac{1}{n}\ V_s(t)$$

- A) Center-tapped transformer full-wave **Rectifier**
- V_A , V_B have the same amplitude but 180° out of phase



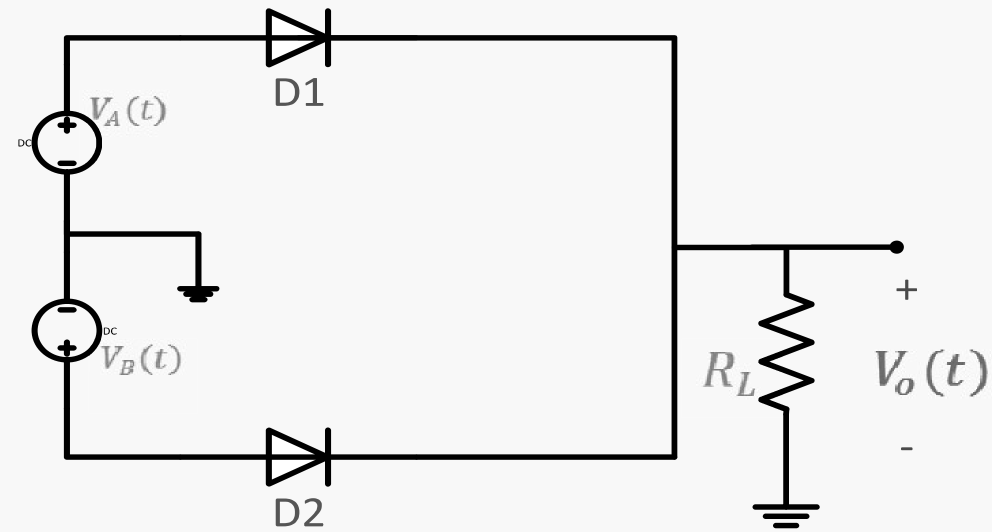


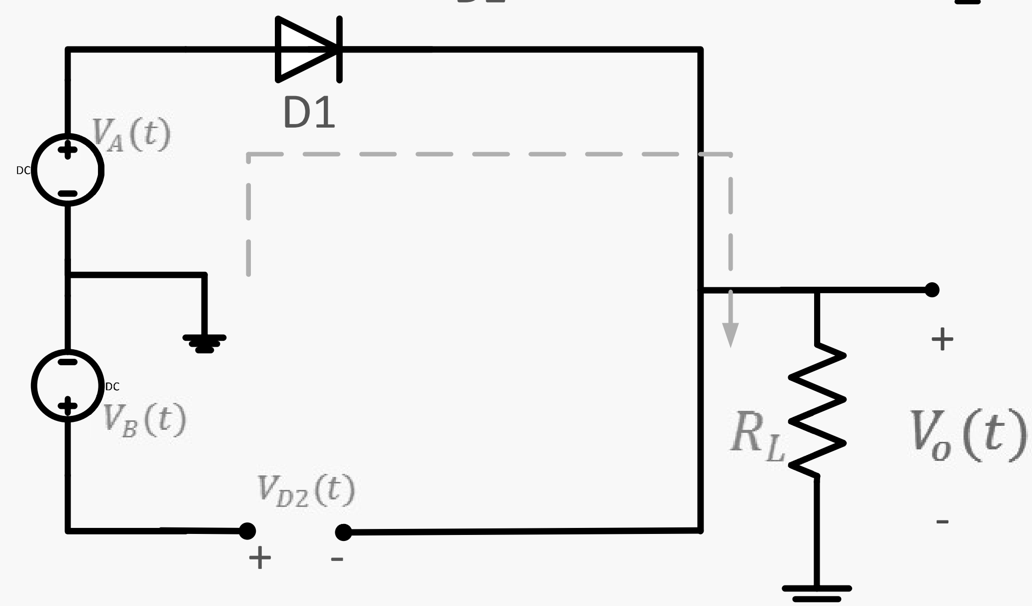
Simplified Circuit

- 1) when $V_s(t) > 0$

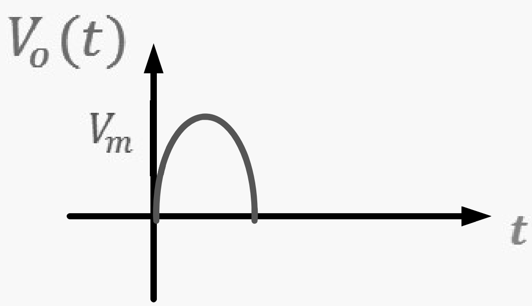
  $V_A(t) > 0$, D_1 is on

  $V_B(t) < 0$, D_2 is off





- $V_o(t) = V_A(t)$



- $V_{D2}(t) = V_B(t) - V_A(t)$

  $V_{D2}(t)_{,max} = -V_m - V_m$

  $V_{D2}(t)_{,max} = -2V_m$

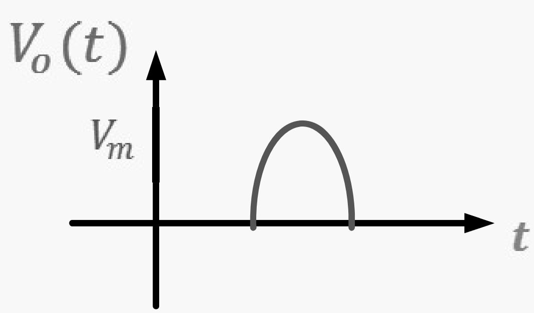
  ∴ PIV = $-2V_m$

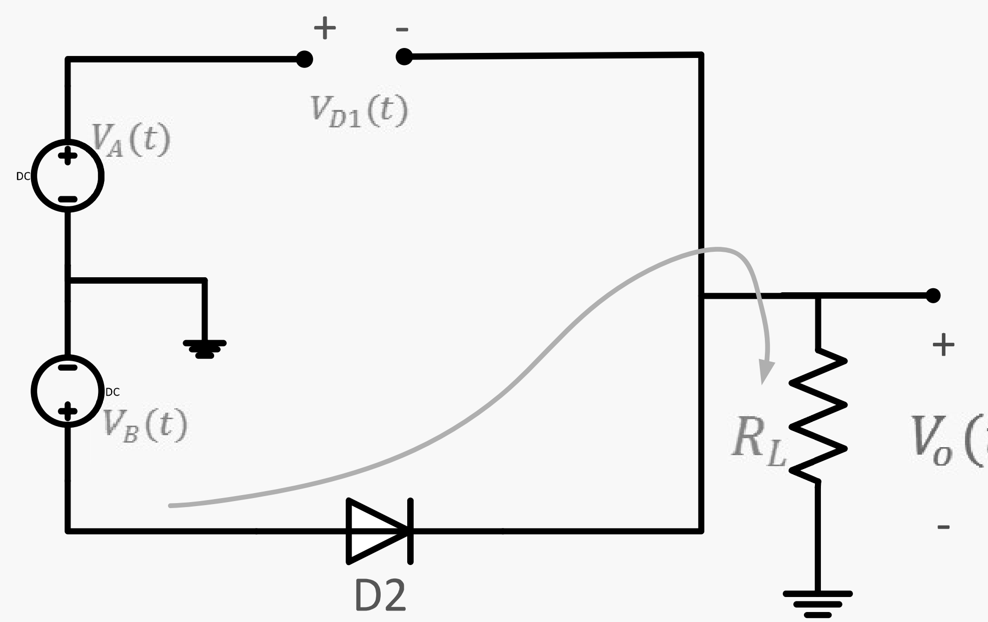
- 2) when $V_s(t) < 0$

  $V_A < 0$; D_1 is off

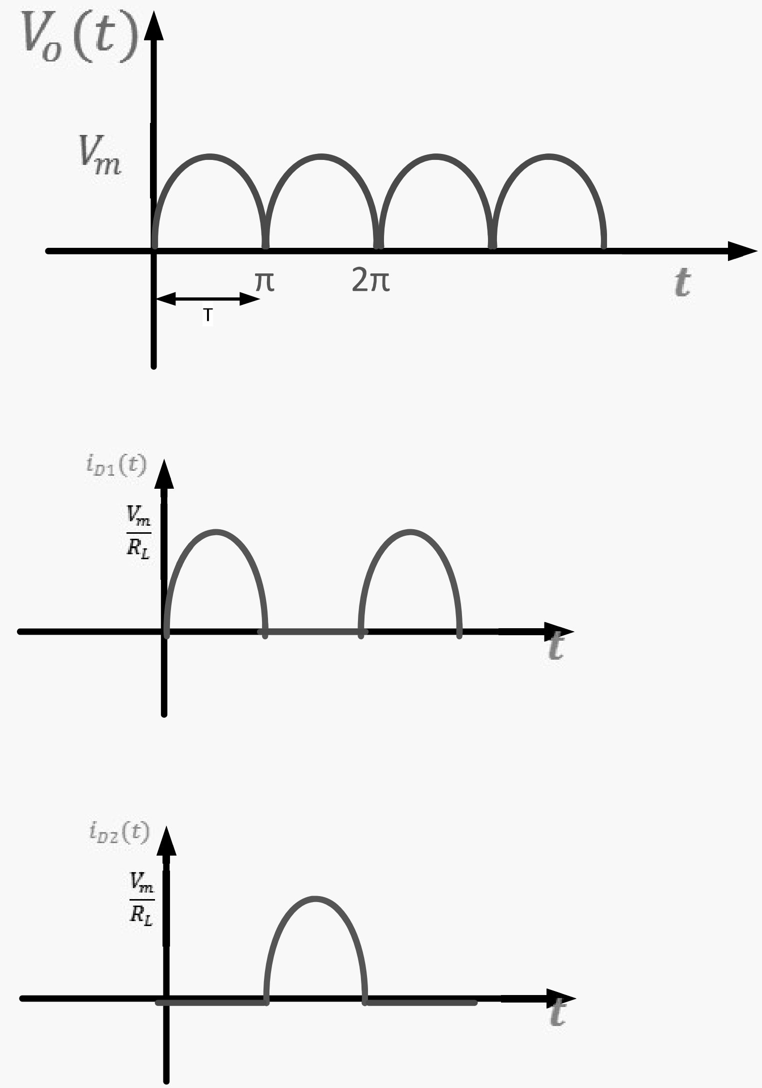
  $V_B > 0$; D_2 is on

- ∴ $V_o(t) = V_B(t) > 0$

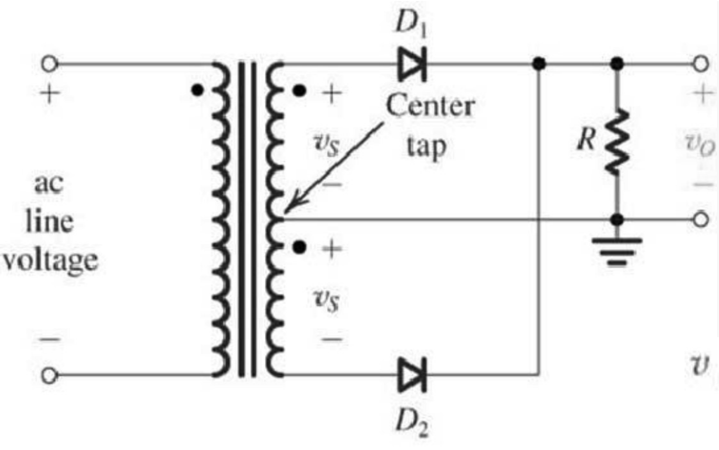




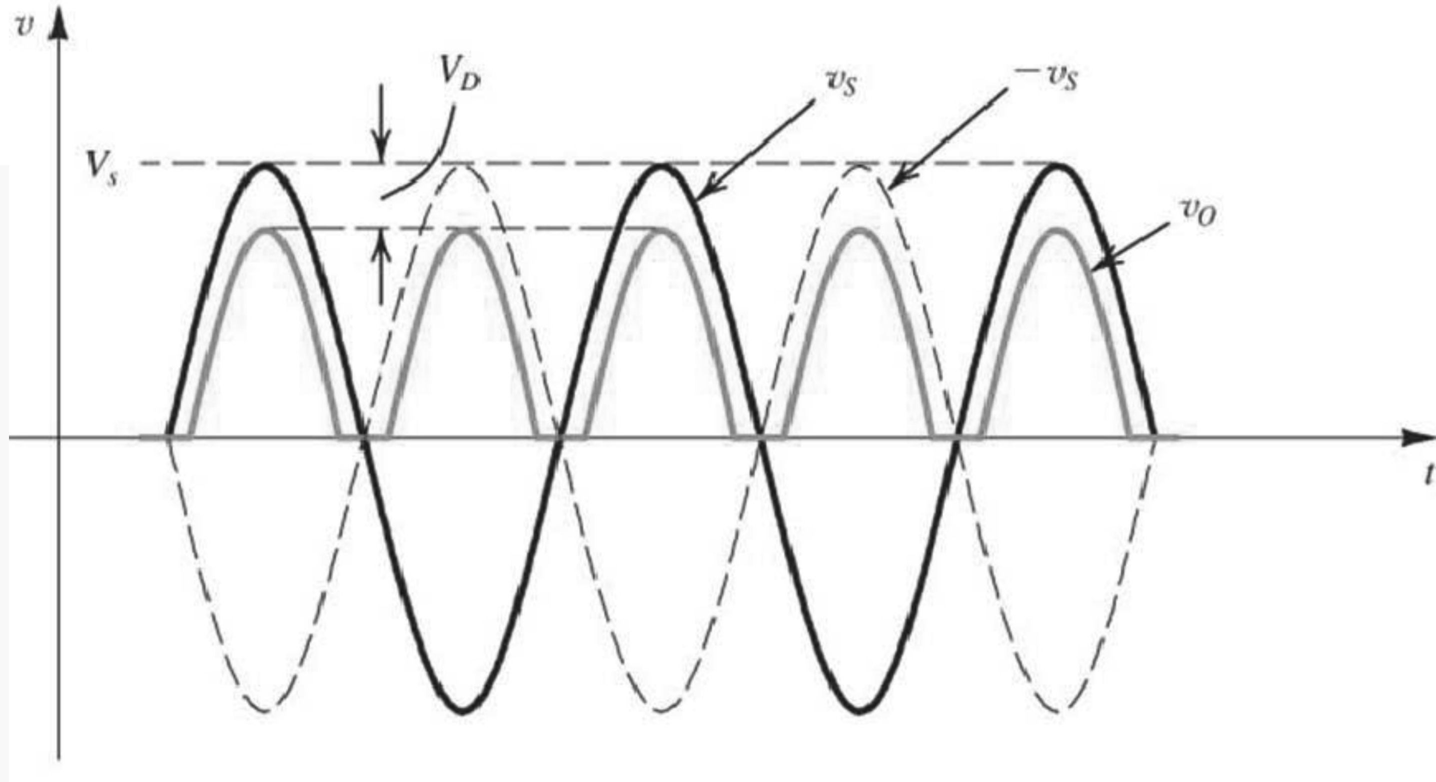
- For a complete cycle of $V_s(t)$
- $V_{o,av} = \frac{2V_m}{\pi}$
- PIV = $-2V_m$
- $\mathrm{T} = \frac{1}{2}T_o$
- $f = 2\,f_o$



If the diodes have Vk



(a)



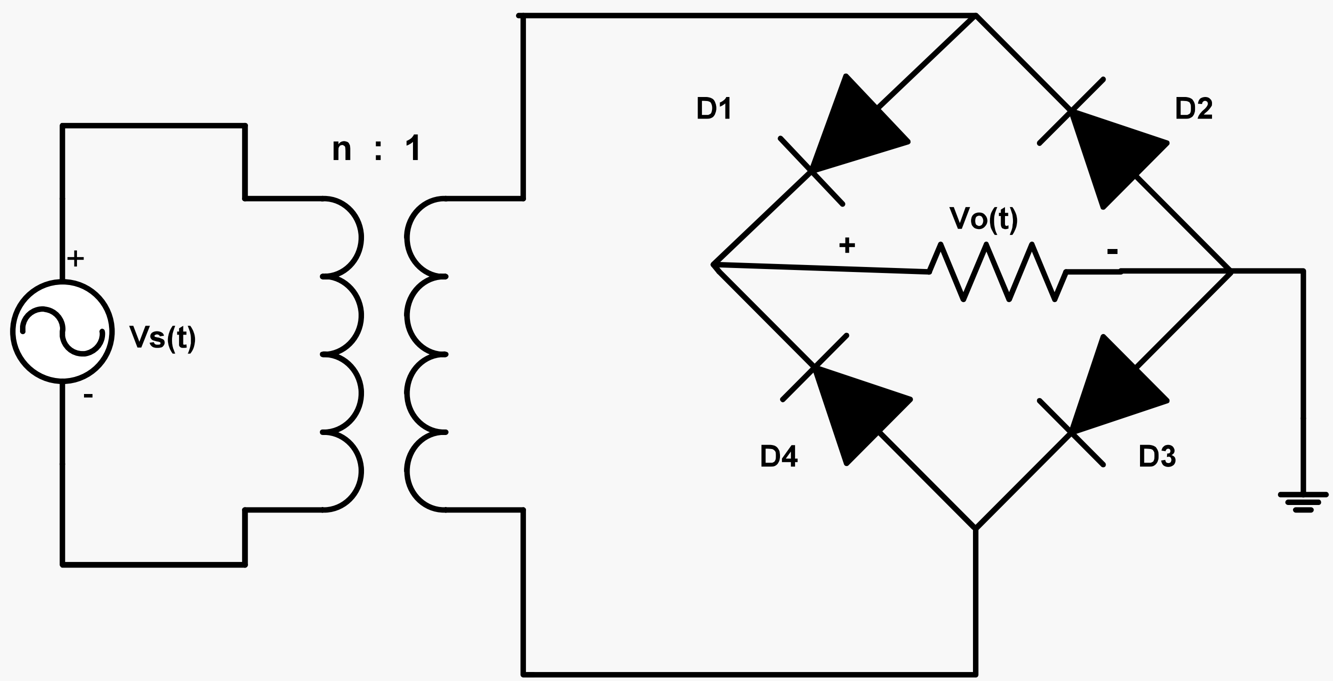
(c)

Dc Power Supply

Bridge Full Wave Rectifier

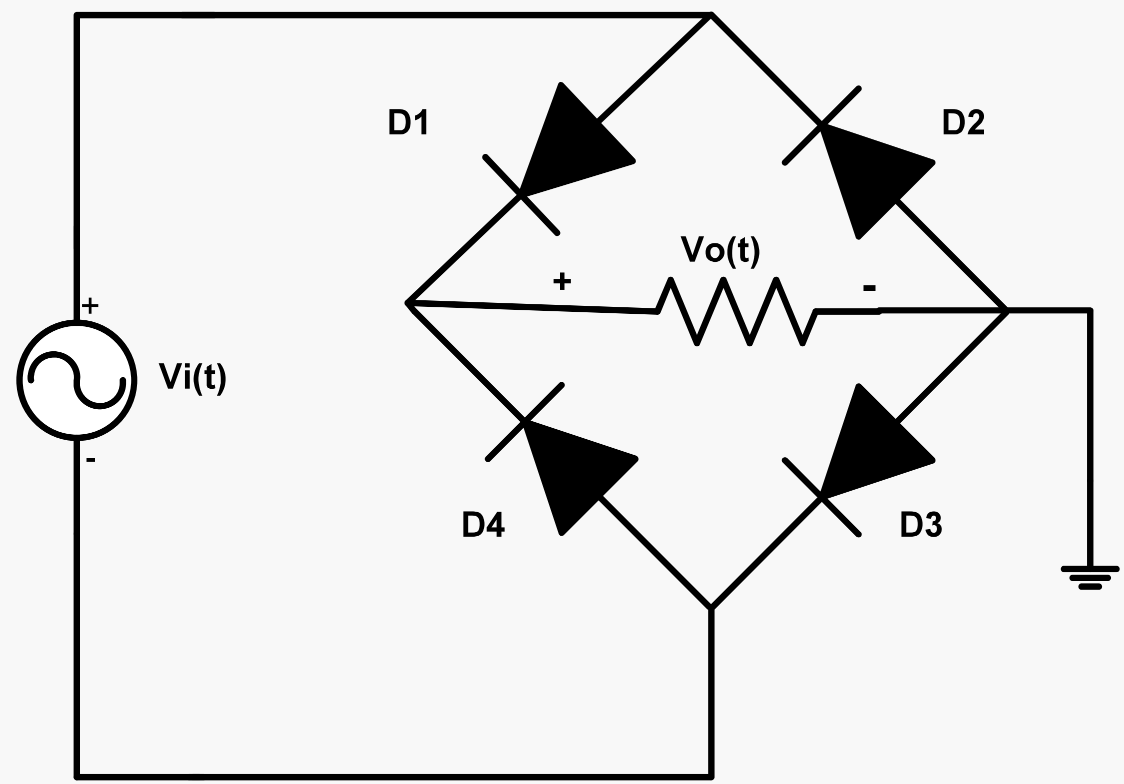
Filter

b) Bridge full-wave rectifier



b) Bridge full-wave rectifier

- Simplified circuit



b) Bridge full-wave rectifier

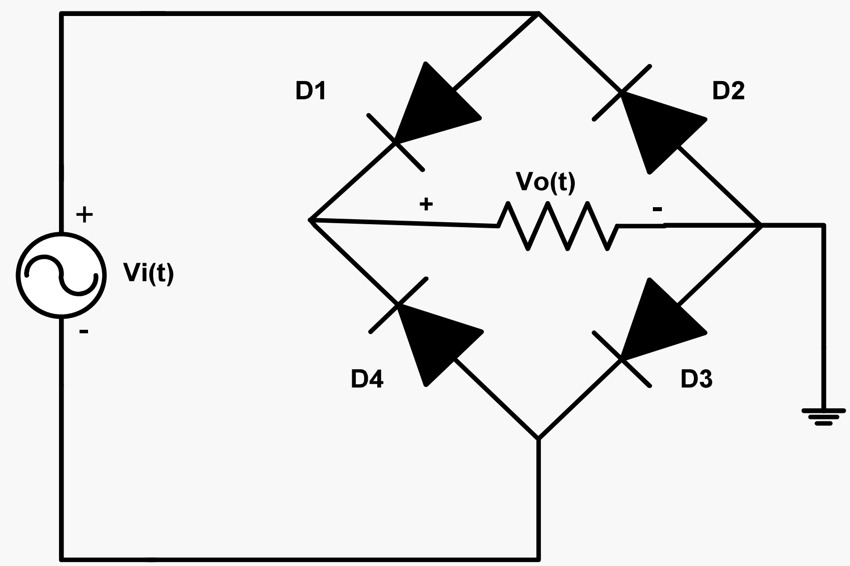
- 1) **when $V_s(t) > 0$**

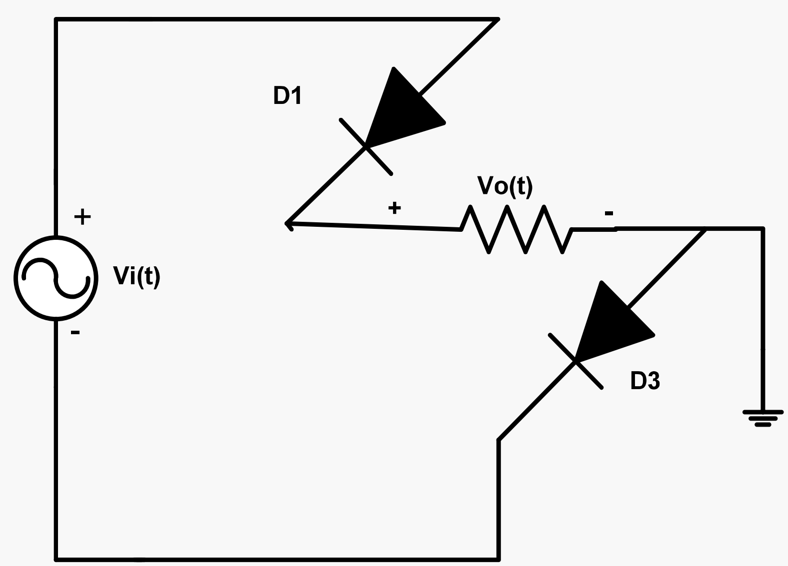
  $\therefore V_i(t) > 0$

  $\therefore$ D_1 **and** D_3 **are on**

  $\therefore$ D_2 **and** D_4 **are off**

- $V_o(t) = V_i(t)$





▸ 2) when $V_s(t) < 0$

$\therefore V_i(t) < 0$

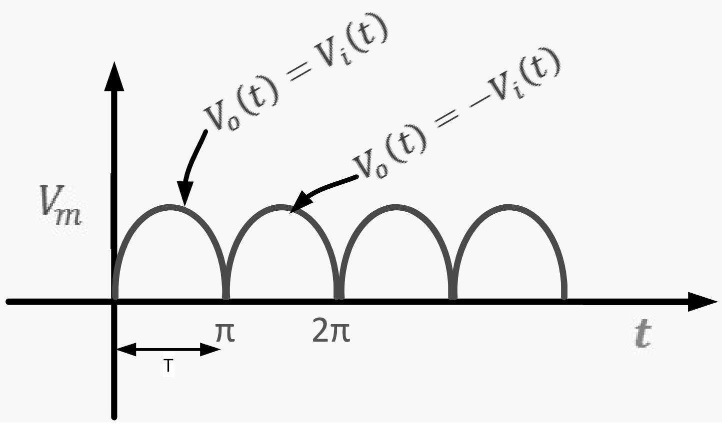
$\therefore$ D_1 and D_3 are off

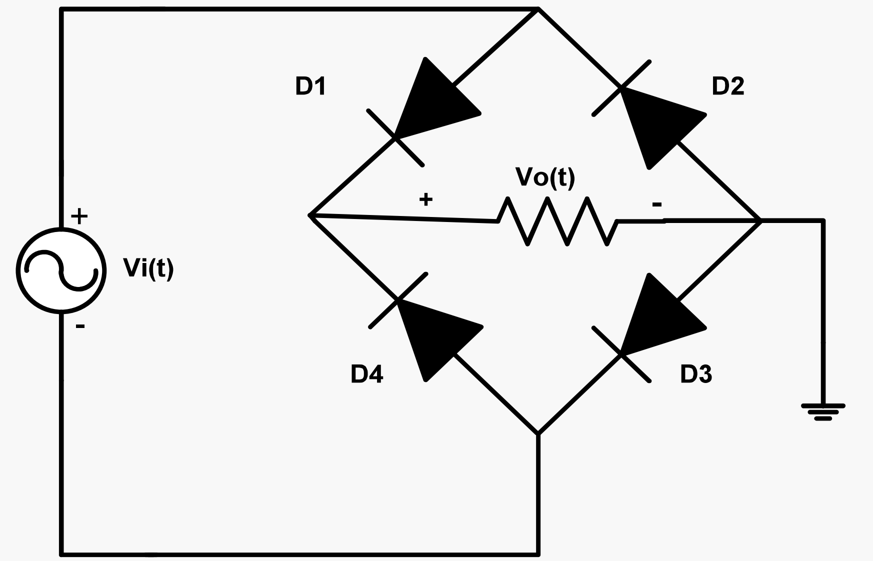
$\therefore$ D_2 and D_4 are on

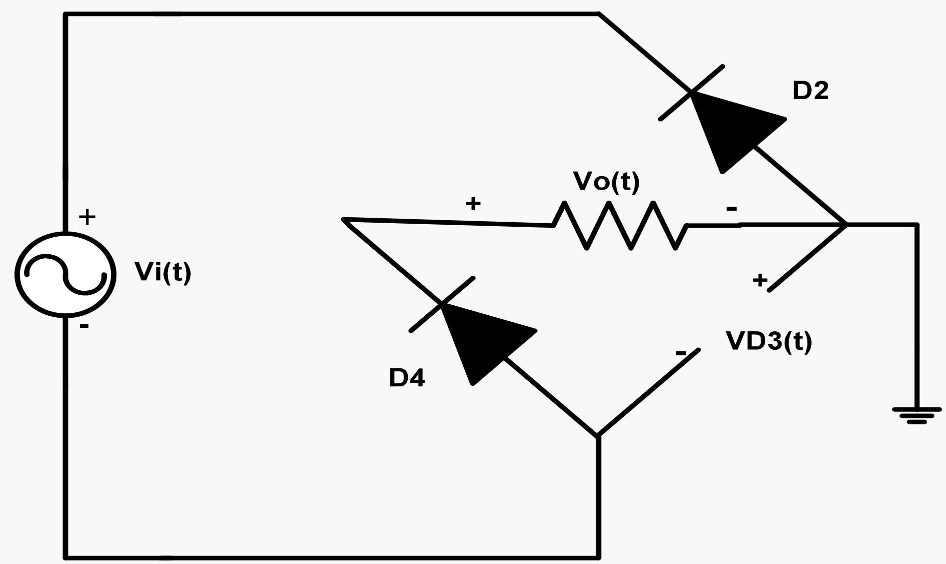
$\therefore V_o(t) = -V_i(t)$

$\therefore V_{D3}(t) = V_i(t) < 0$

$\therefore$ For the complete cycle of $V_i(t)$

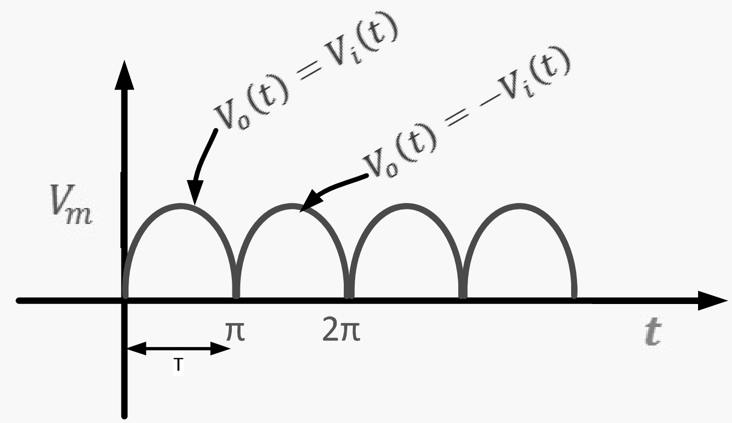






- $\therefore$ For Bridge full-wave rectifier
- $V_{o,av} = \frac{1}{T} \int_0^T V_o(t)dt$

  $V_{o,av} = \frac{2V_m}{\pi}$
- $T = \frac{1}{2} T_o$
- $f = 2f_o$

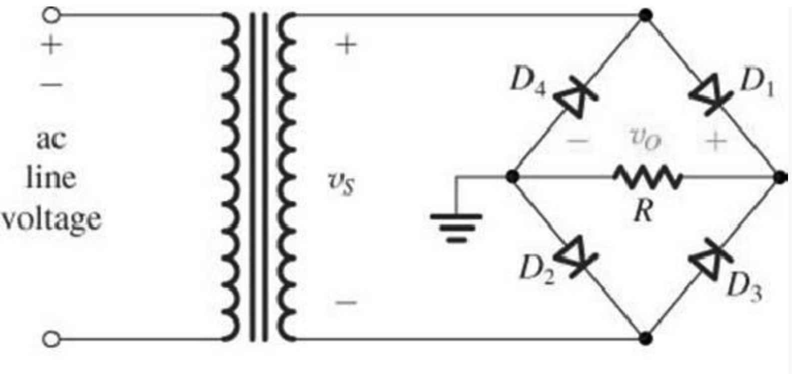


- To calculate the PIV When $V_i(t) < 0$

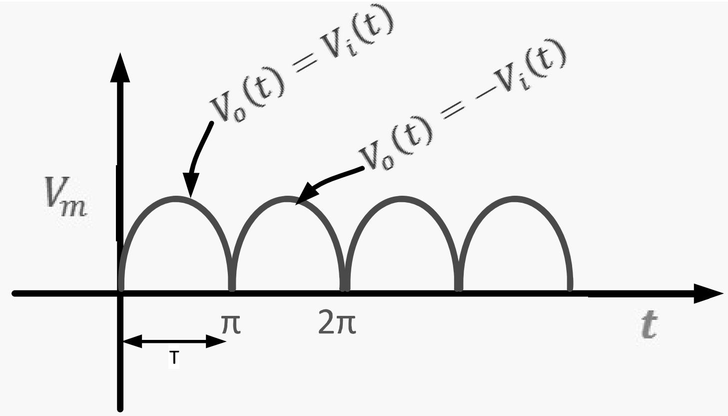
  $V_{D3}(t) = V_i\ (t)$

  $\therefore\ V_{D3}(t)_{,max} = -V_m$

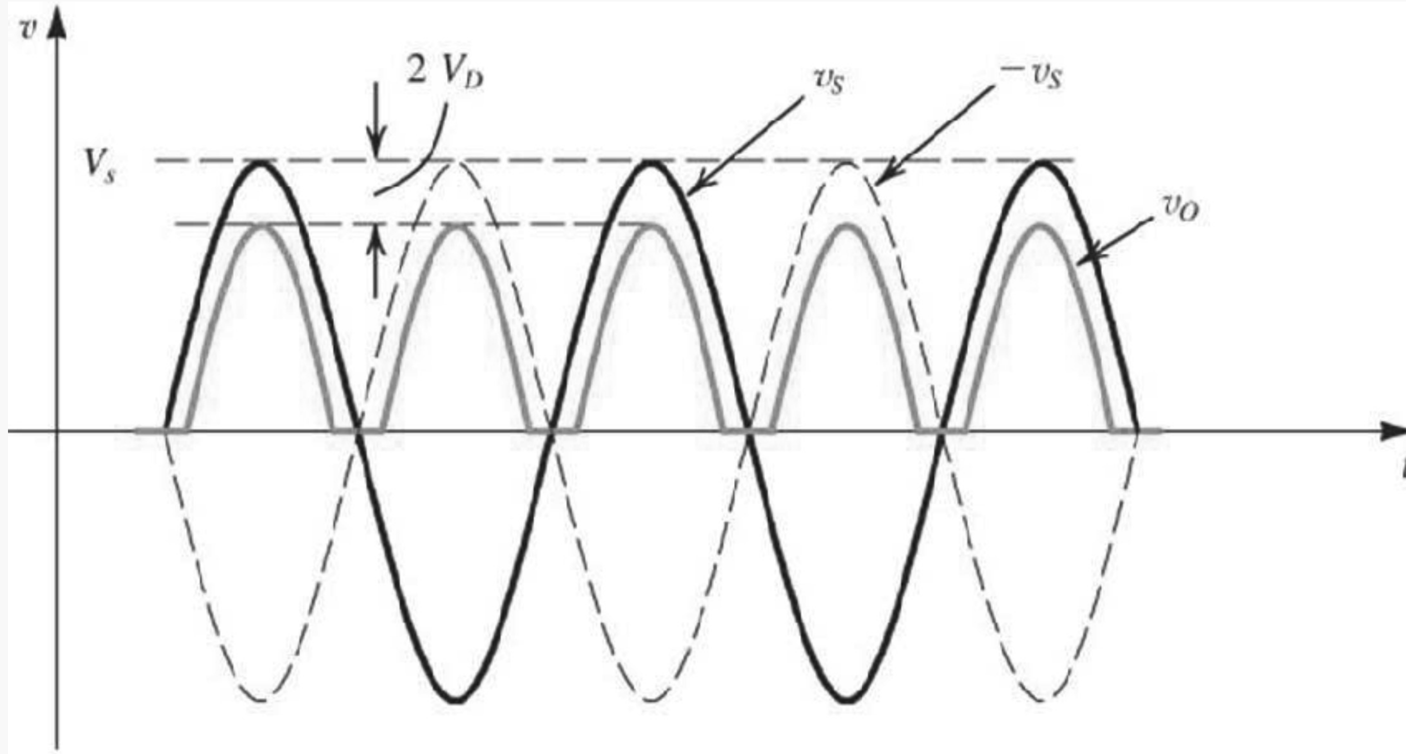
  $\therefore$ PIV $= -V_m$



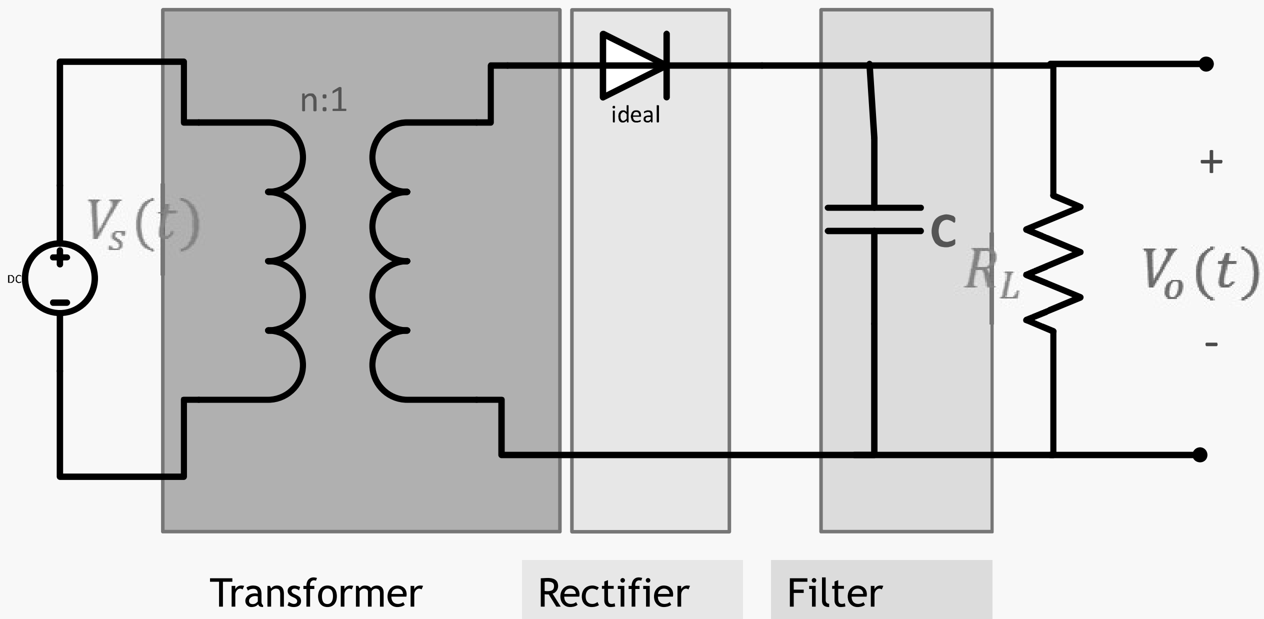
(a)



If the diodes have Vk



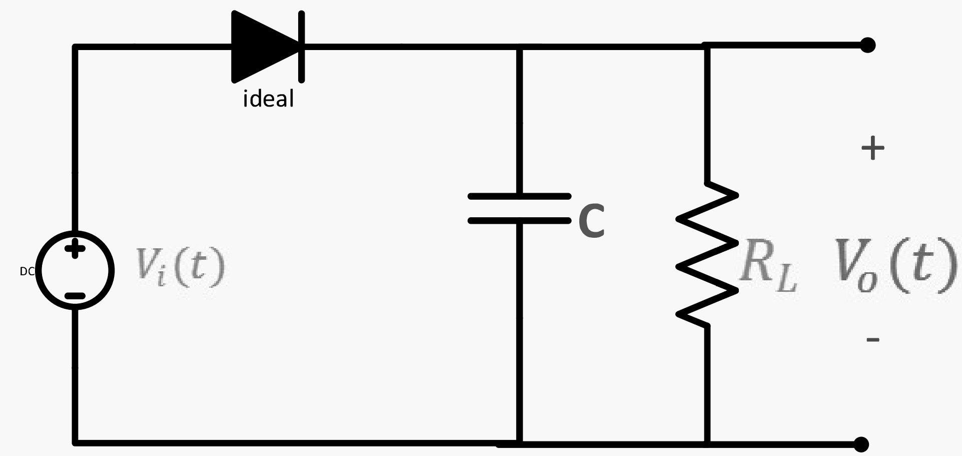
- Filter: **used to smooth out the pulsating dc produced by the rectifier by removing its ac ripple contents and passing its dc component (average value)**

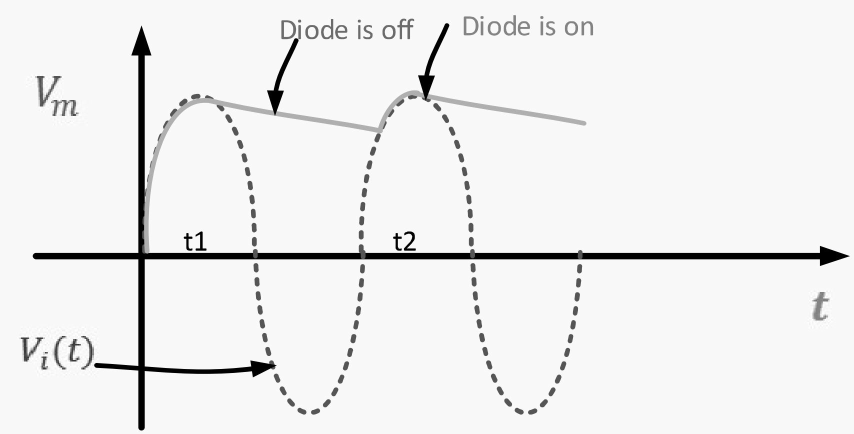


Simplified Circuit

- **A) when $V_i(t) > V_c(t)$; Diode is on and $V_l(t) = V_c(t) = V_i(t)$**

- **B) when $V_i(t) < V_c(t)$; Diode is off and the capacitor starts discharging**

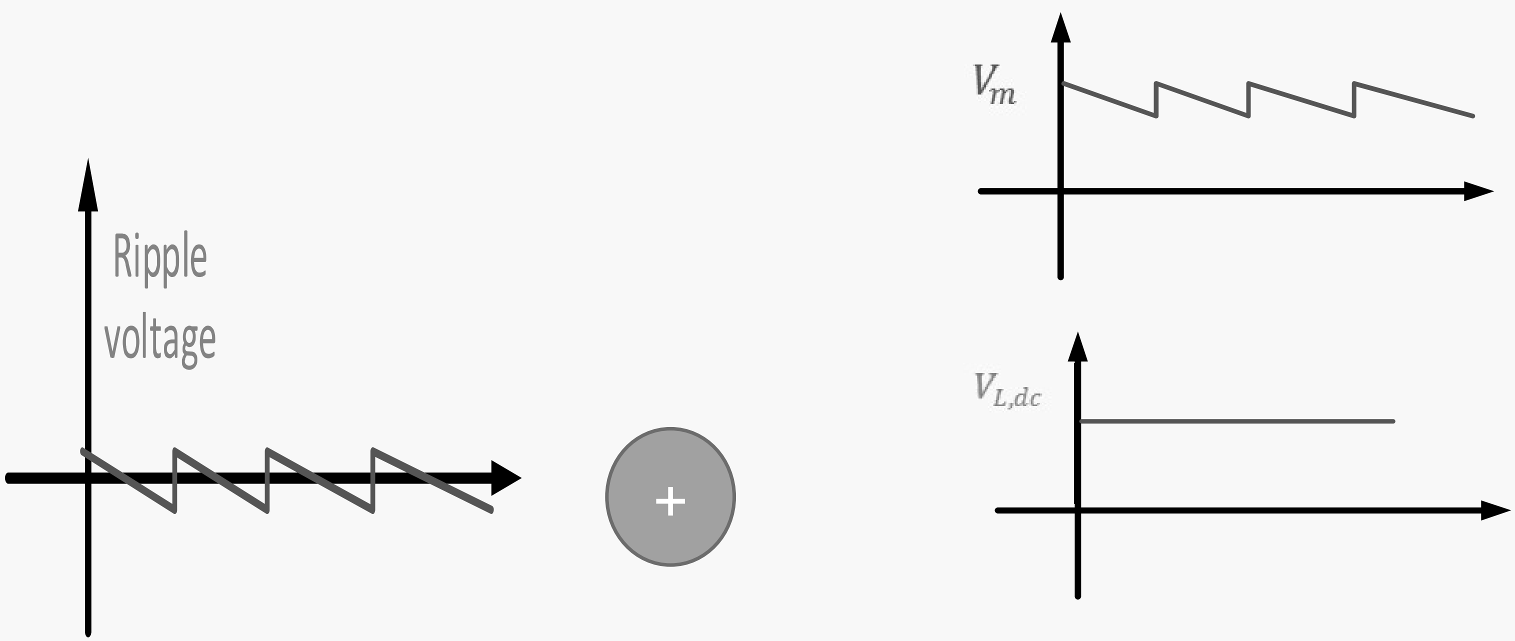




- Ripple factor is an indicator for the effectiveness of the filter

$$r = \frac{RMS(ripple\ voltage)}{Average\ value\ of\ the\ output\ signal} \times 100\%$$

- The output signal can be approximated as shown



Example

- $V_{L,dc} = V_{L,av} = \frac{1}{T} \int_0^T V_L(t)dt$

  $V_{L,dc} = \frac{1}{T}$. area

  $= \frac{1}{T}(8T + \frac{2.T}{2})$

  $V_{L,dc} = 9\ V$

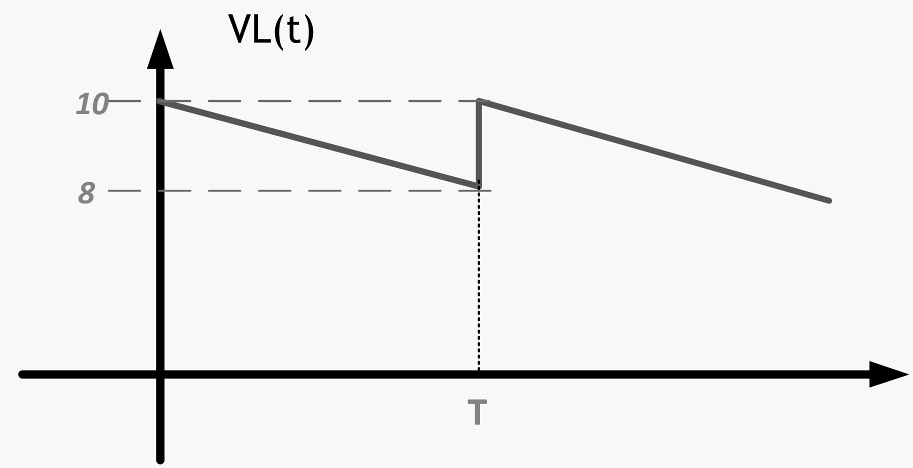
OR

- $V_{L,dc} = V_m - \frac{1}{2} V_{Lr,p-p}$

  where $V_m = 10\ V$

  $V_{Lr,p-p} = 2$ V p-p

  $\therefore V_{L,dc} = 10 - \frac{1}{2}(2) = 9V$



- Also for a triangle signal, the $RMS\ value = \frac{Peak\ Value}{\sqrt{3}}$

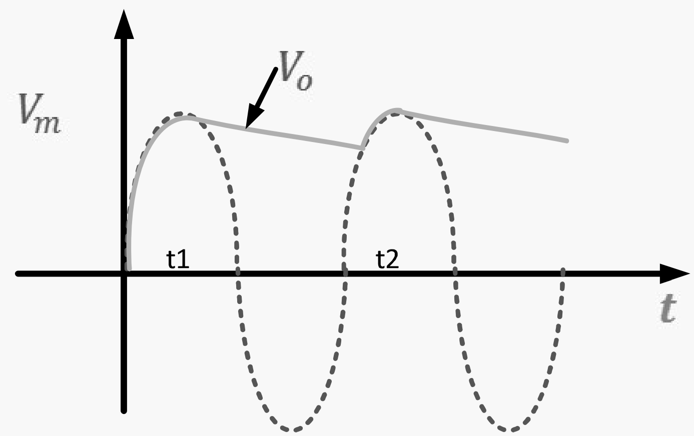
or $RMS\ value = \frac{Peak\text{−}to\text{−}peak\ Value}{2\sqrt{3}}$

$$= \frac{V_{Lr,p-p}}{2\sqrt{3}}$$

$$\therefore r = \frac{\frac{V_{Lr,p-p}}{2\sqrt{3}}}{V_m - \frac{1}{2}V_{Lr,p-p}} \times 100\%$$

$\therefore$ To determine the ripple factor we need to find $V_{Lr,p-p}$

Ripple Factor



- For $t_2 > t > t_1$
- $V_L(t) = V_m \, e^{-(t-t_1)/RC}$
- $V_{Lr,p-p} = V_L(t_1) - V_L(t_2)$
- $V_{Lr,p-p} = V_m \; - V_m \; e^{-(t_2-t_1)/RC}$
- $V_{Lr,p-p} = V_m \, (1 - e^{-\frac{(t_2-t_1)}{Rc}})$

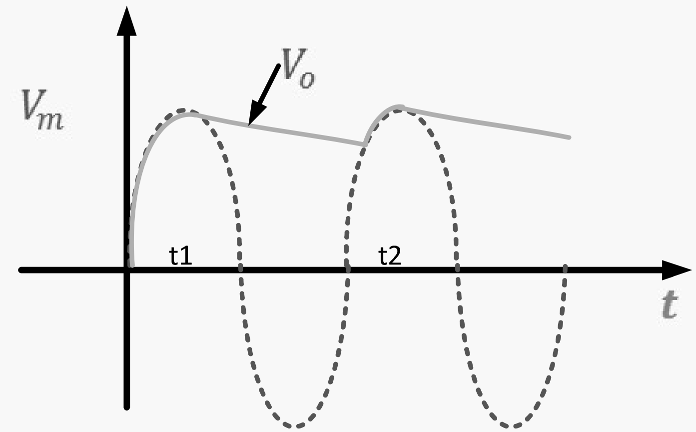
  Using $e^{-x} \cong 1 - x$
- $V_{Lr,p-p} = \frac{V_{m(t_2-t_1)}}{R\,C}$
- $V_{L,dc} = V_m - \frac{1}{2} V_{Lr,p-p}$

- For half-wave rectifier
- $t_2 - t_1 = T_o = \frac{1}{f_o}$

  $\therefore V_{Lr,p-p} = V_m \frac{1}{f_o R\,C}$
- $V_{L,dc} = V_m\left(1 - \frac{1}{2 f_o R\,C}\right)$
- $\left(V_{L,r}\right)_{rms} = \frac{V_{Lr,p-p}}{2\sqrt{3}}$

  $\left(V_{L,r}\right)_{rms} = \frac{V_m}{2\sqrt{3} f_o R\,C}$
- $r = \frac{\left(V_{L,r}\right)_{rms}}{V_{L,dc}} \times 100\%$

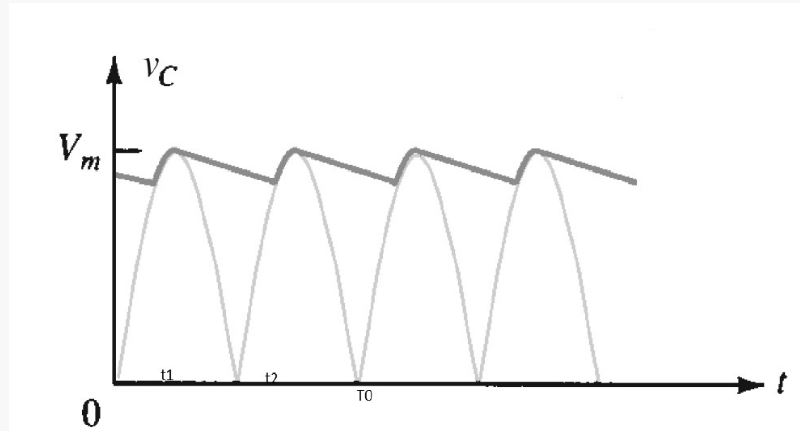
  $r = \frac{1}{\sqrt{3}(2 f_o R\,C \;\; -1)} \times 100\%$



- For full-wave rectifier
- $t_2 - t_1 \approx \frac{1}{2} T_o = \frac{1}{2f_o}$

  $\therefore V_{Lr,p-p} = V_m \frac{1}{2f_oRC}$
- $V_{L,dc} = V_m\left(1 - \frac{1}{4f_oRC}\right)$

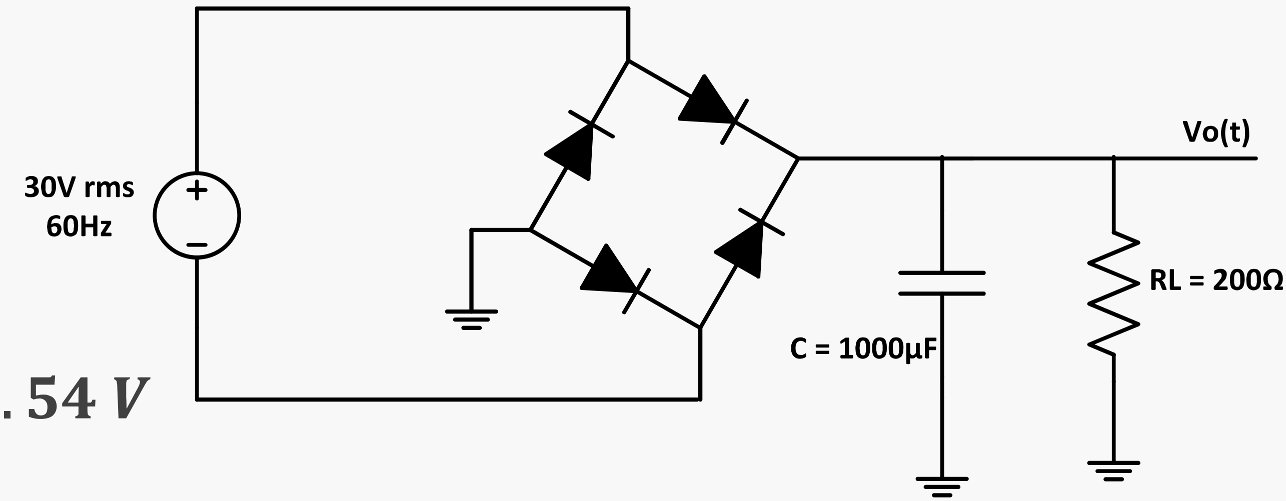
  $\left(V_{L,r}\right)_{rms} = \frac{V_m}{4\sqrt{3} f_oRC}$



$$r = \frac{1}{\sqrt{3}(4f_oRC - 1)} \times 100\%$$

Example

- Find the ripple factor r



- $V_{L,dc} = V_m - \frac{1}{2}\frac{V_m}{2f_o R_L C} = 41.54\ V$
- $V_{Lr,p-p} = \frac{V_m}{2f_o R_L C} = 1.7677\ V$
- RMS (ripple voltage) $= \frac{V_{Lr,p-p}}{2\sqrt{3}} = 0.51V\ rms$

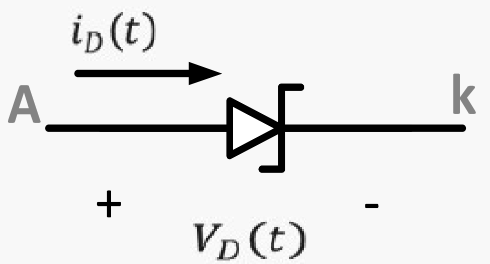
$\therefore r = \frac{0.51}{41.54} \times 100\%$

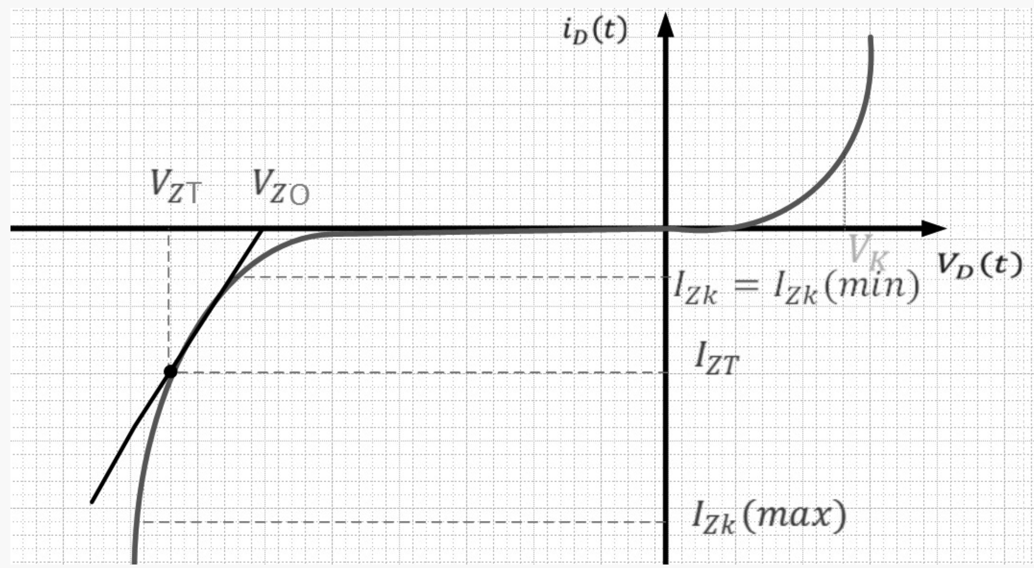
$r = 1.2277\ \%$

Zener Diode

Simple voltage regulator

Zener Diode





The model of the Zener Diode in the breakdown

- $r_Z = \dfrac{\Delta V_Z}{\Delta I_Z}$

Example

A 1N4736 zener diode has $r_z = 3.5\ \Omega$, the data sheet given

$V_{ZT} = 6.8$v @ $I_{ZT} =$ **37**mA

and $I_{ZK} = 1$mA .

a) Find V_Z when I_Z =50mA

b) Find V_Z when I_Z =25mA

▸ solution

$$V_Z = r_z\, I_Z + V_{ZO}$$
$$V_{ZT} = r_z\, I_{ZT} + V_{ZO}$$
$$6.8\text{v} = (3.5)(37\text{mA}) + V_{ZO}$$
$$V_{ZO} = 6.6705\text{v}$$

a) when I_Z =50mA

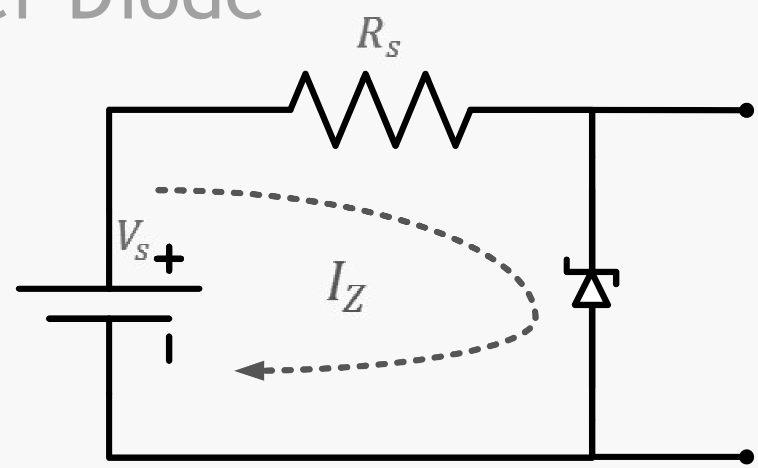
$$V_Z = (3.5)(50\text{mA}) + 6.6705$$
$$V_Z = 6.8455\text{v}$$

b) when I_Z =25mA

$$V_Z = (3.5)(25\text{mA}) + 6.6705$$
$$V_Z = 6.756\text{v}$$

Circuits Containing Zener Diode

* Zener diode is reversed bias



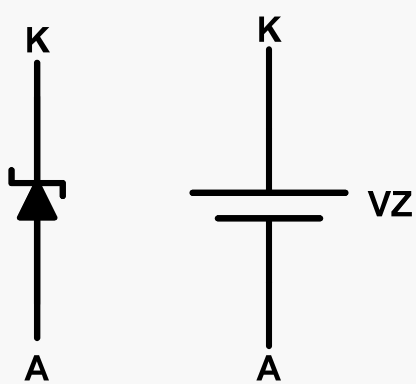
- If $V_S > \boldsymbol{V_{ZO}}$, the zener diode is in the breakdown region .
- If $V_S < \boldsymbol{V_{ZO}}$, the zener diode is open circuit.

Also we must make sure that

- $I_Z(\text{max}) > \boldsymbol{I_Z} > I_Z(\text{min})$

For the zener diode to operate safely in the breakdown region .

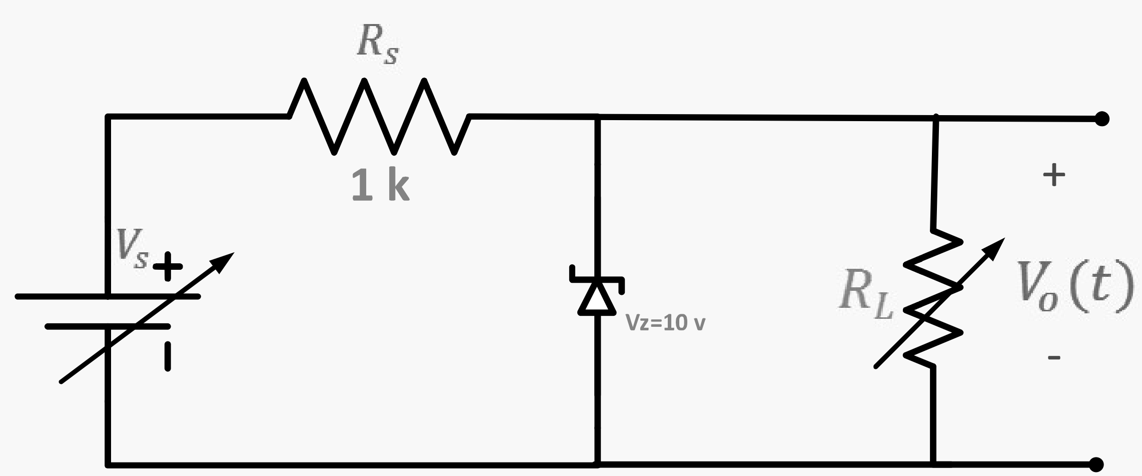
Ideal model of Zener in the breakdown region .



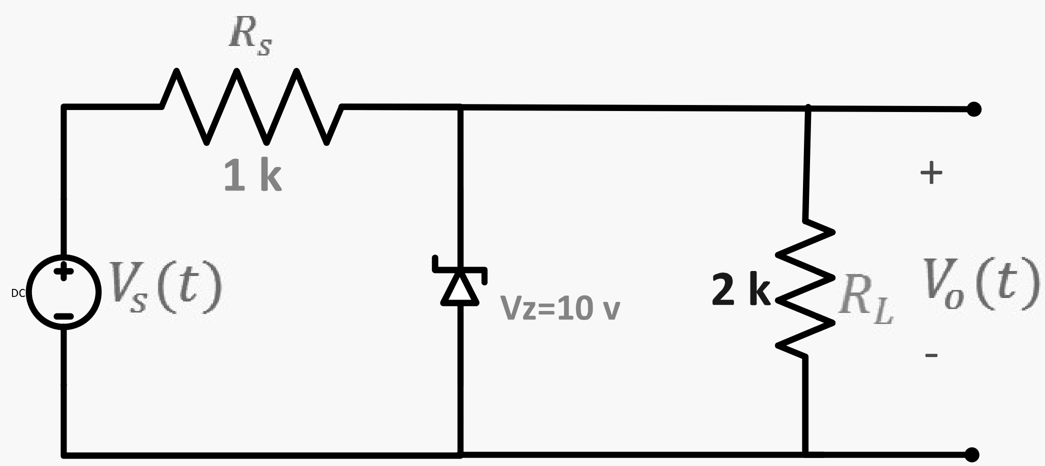
Regulator :

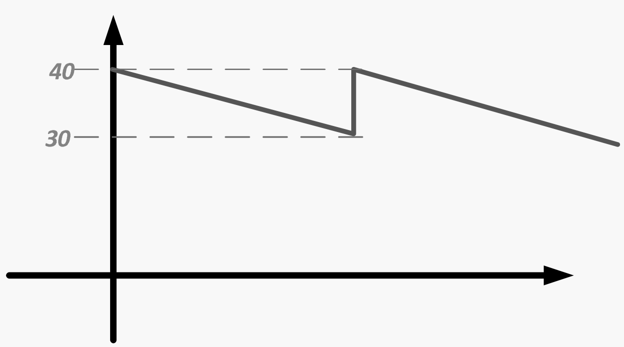
Used to maintain a constant dc output voltage under variation in the load current from the dc power supply and under variation in the ac line voltage

Simple voltage regulator

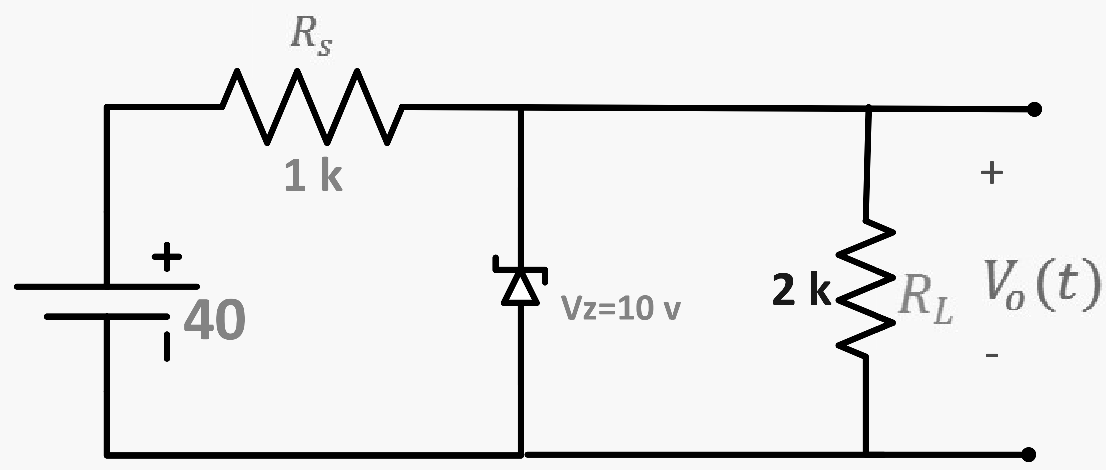


Voltage regulation with input variation



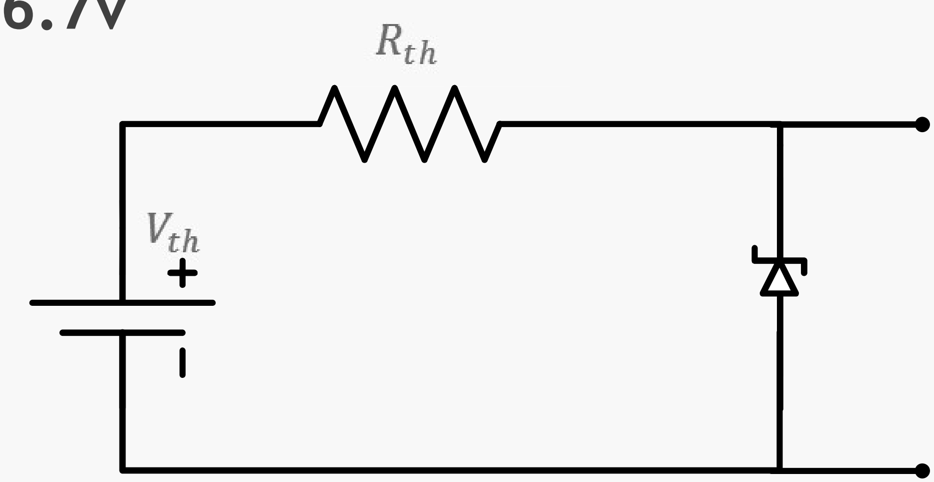


a) Let V_S(t) = 40V

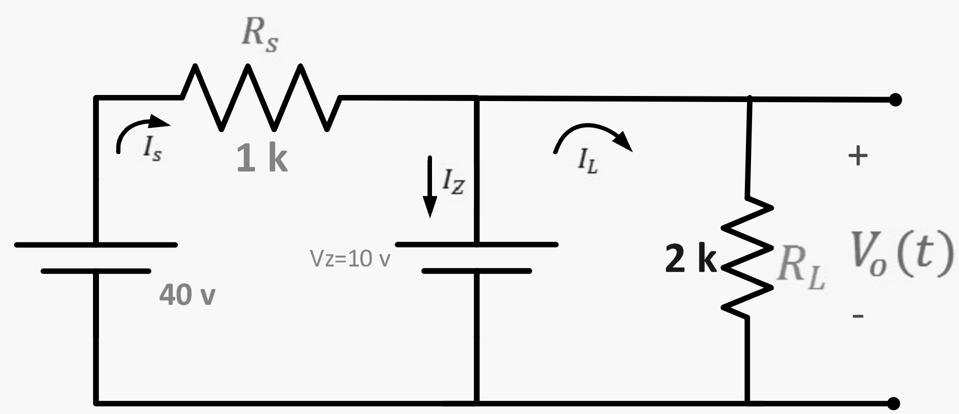


R_{TH}= 1K \\ 2K = 0.67 k

V_{TH}= $\frac{2K}{2K+1K}$. 40 = 26.7v



▸ **Since** $V_{TH} > V_Z$; **the Zener diode is in the breakdown region .**



$$\therefore \; V_O = V_Z = 10\text{v}$$

$$I_S = \frac{40-10}{1K} = 30 \text{ mA}$$

$$I_L = \frac{V_O}{R_L} = 5\text{mA}$$

$$I_Z = I_S - I_L = 25\text{mA}$$

b) Let V_S(t) = 30v

- Following the same steps as before

  R_{TH} = 0.67K

  V_{TH} = 20v

- Since $V_{TH} > V_Z$; the zener in the breakdown

$\therefore$ V_O = V_Z = 10v

I_S = 20 mA

I_L = = 5mA

I_Z = 15mA

2) Voltage regulation with load variation

a) Let R_L = 0.5K

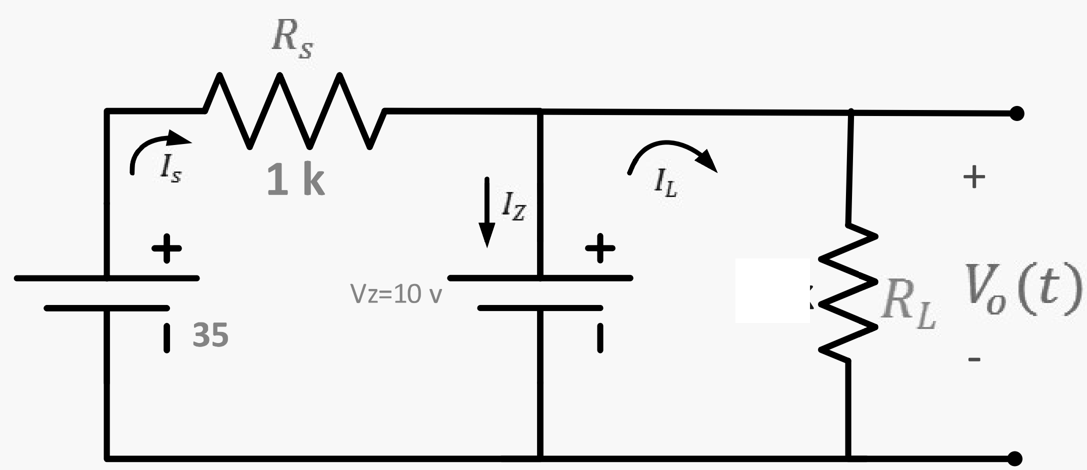
the zener diode is in the breakdown region . Prove !!

$V_O = V_Z = 10v$

$I_S = \frac{35-10}{1K} = 25\ mA$

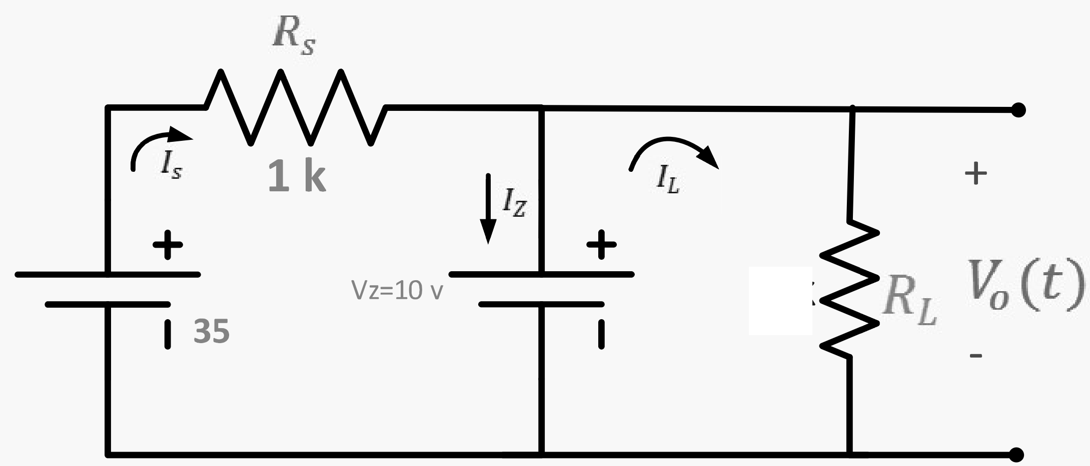
$I_L = \frac{V_O}{R_L} = 20mA$

$I_Z = I_S - I_L = 5mA$



b) Let R_L= 5K

- the Zener diode is in the breakdown region . Prove !!



$V_O = V_Z = 10v$

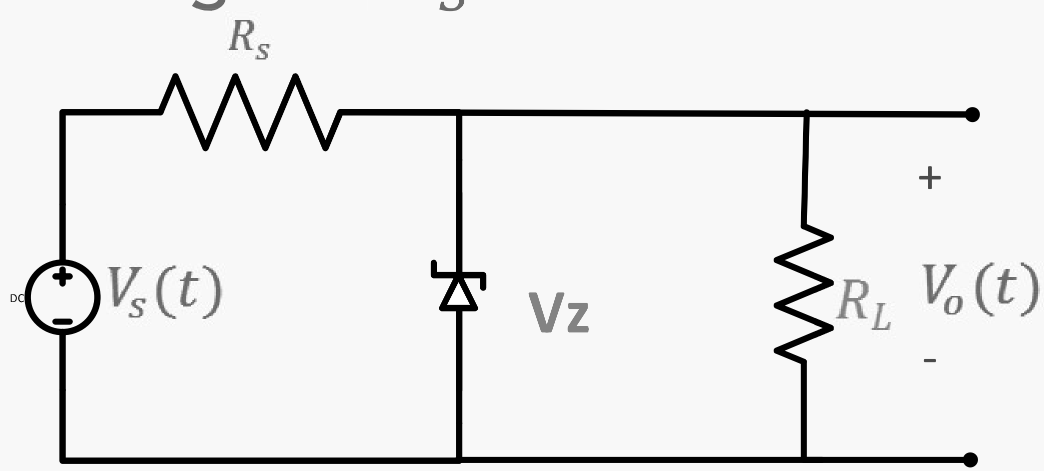
$I_S = \frac{35-10}{1K} = 25\ mA$

$I_L = \frac{V_O}{R_L} = 2mA$

$I_Z = I_S - I_L = 23mA$

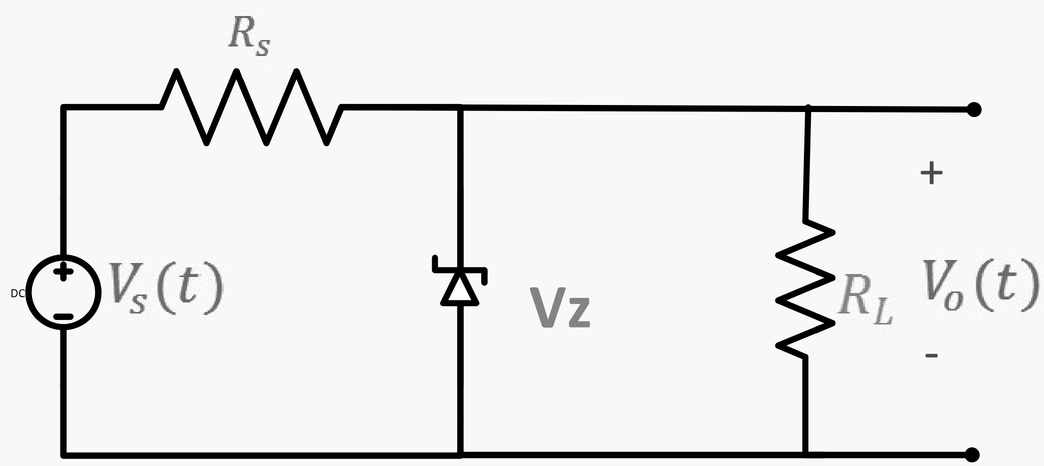
- In the four cases we must verify
- $I_Z(\text{max}) > I_Z > I_Z(\text{min})$

Design of R_S



- Given : V_S(min) and V_S(max)
  R_L(min) and R_L(max)

and (V_Z, I_Z(min) ,I_Z(max))



▸ $I_Z = I_S - I_L$

$I_Z = \frac{V_S(t) - V_Z}{R_S} - I_L > I_Z(\text{min})$

▶ the worst condition

$\frac{V_S(\text{min}) - V_Z}{R_S} - I_L(\text{max}) > I_Z(\text{min})$

$\therefore R_S < \frac{V_S(\text{min}) - V_Z}{I_L(\text{max}) + I_Z(\text{min})}$

now

$I_Z = \frac{V_S(t) - V_Z}{R_S} - I_L < I_Z(\text{max})$

▸ the worst condition

$\frac{V_S(\text{max}) - V_Z}{R_S} - I_L(\text{min}) < I_Z(\text{max}$

$\therefore R_S > \frac{V_S(\text{max}) - V_Z}{I_L(\text{min}) + I_Z(\text{max})}$

Combining the two results

$$\frac{V_S(\text{min}) - V_Z}{I_L(\text{max}) + I_Z(\text{min})} > R_S > \frac{V_S(\text{max}) - V_Z}{I_L(\text{min}) + I_Z(\text{max})}$$

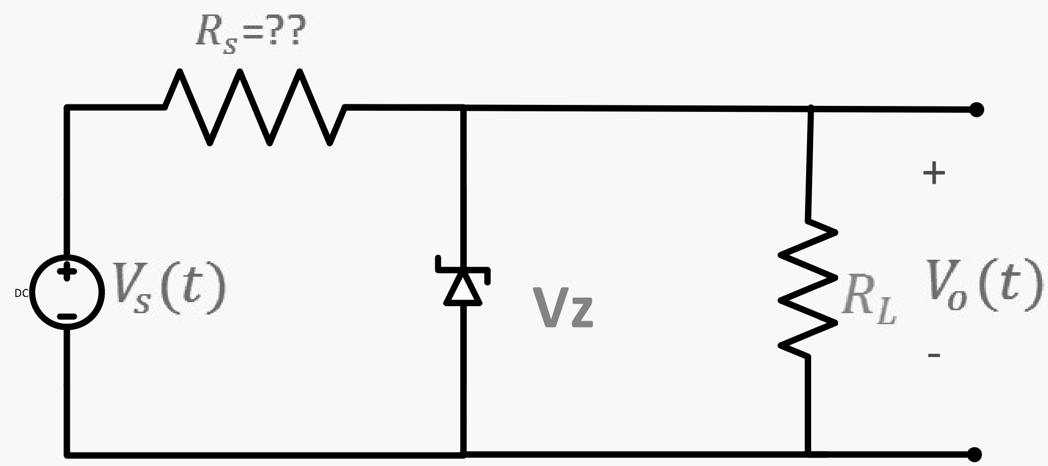
note that

$$I_L(\text{max}) = \frac{V_Z}{R_L(\text{min})}$$

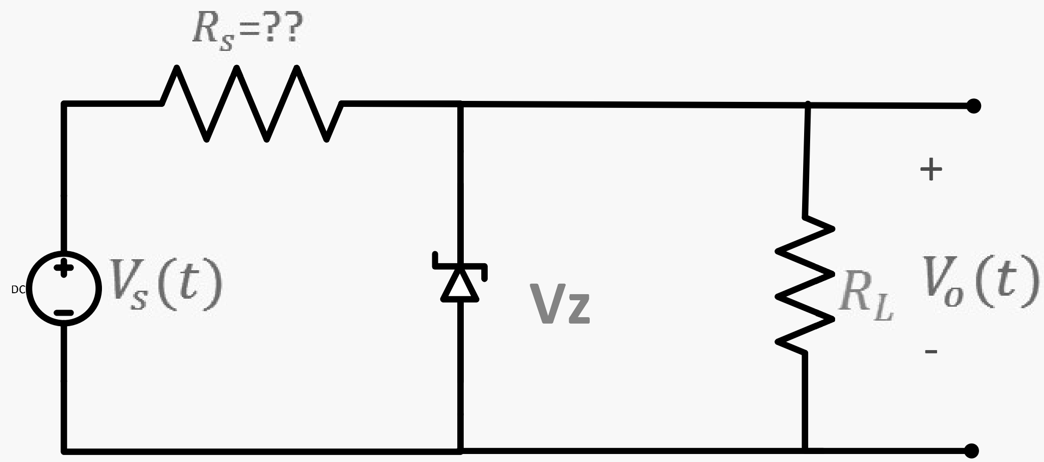
and

$$I_L(\text{min}) = \frac{V_Z}{R_L(\text{max})}$$

Example



- Given :
- Zener diode : I_Z(min)=5mA
  I_Z(max)=200mA
  Vz = 10V
- load: R_L(min)=500 Ω ; ∴ I_l(max)= 20 mA
  R_L(max)= ∞ Ω ; ∴ I_l(min)= 0 mA
- Input signal : V_S(min)=15 v
  V_S(max)=20 v



$$\frac{V_S(\text{min}) - V_Z}{I_L(\text{max}) + I_Z(\text{min})} > R_S > \frac{V_S(\text{max}) - V_Z}{I_L(\text{min}) + I_Z(\text{max})}$$

$$200 > R_S > 50\ \Omega$$

$$\therefore \text{ Let } R_S = 100\ \Omega$$

To determine the effectivener of the voltage regulator ,we define two indicator

a) Load regulation = $\frac{\Delta V_O}{\Delta I_L}$

assuming V_S constant

b) Line regulation = $\frac{\Delta V_O}{\Delta V_S}$

assuming R_L fixed

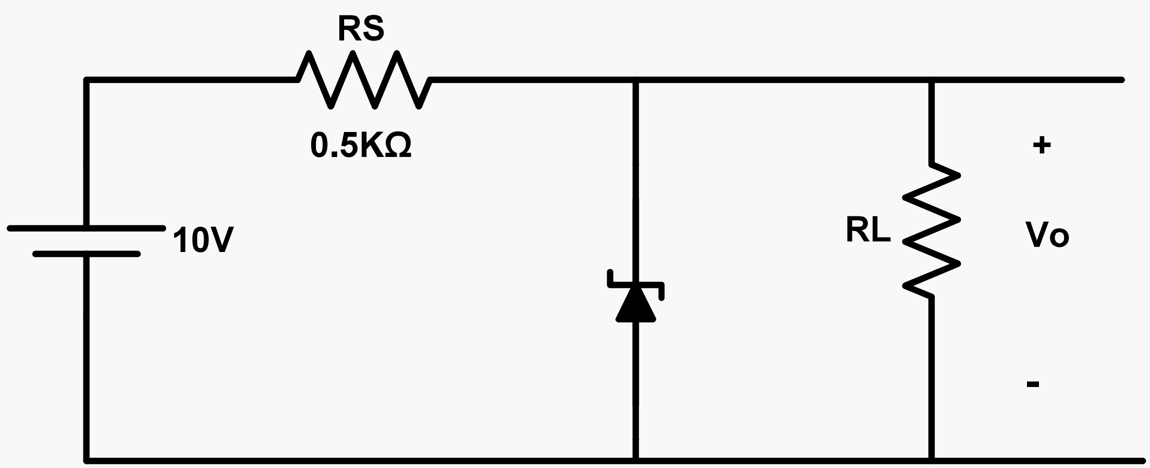
- For the simple voltage regulator , and using ideal model for the zener diode

$\frac{\Delta V_O}{\Delta I_L}$ =0

and $\frac{\Delta V_O}{\Delta V_S}$= 0

$\infty \geq$ RL $\geq$ 2K

a) Load regulation = $\frac{\Delta V_O}{\Delta I_L}$



The zener diode

$V_{ZT} = 6.8\text{ v} \;@\; I_{ZT} = 5\text{mA}$ and $r_z = 20\Omega$

$V_Z = r_z\, I_Z + V_{ZO}$

$V_{ZO} = 6.7\text{v}$

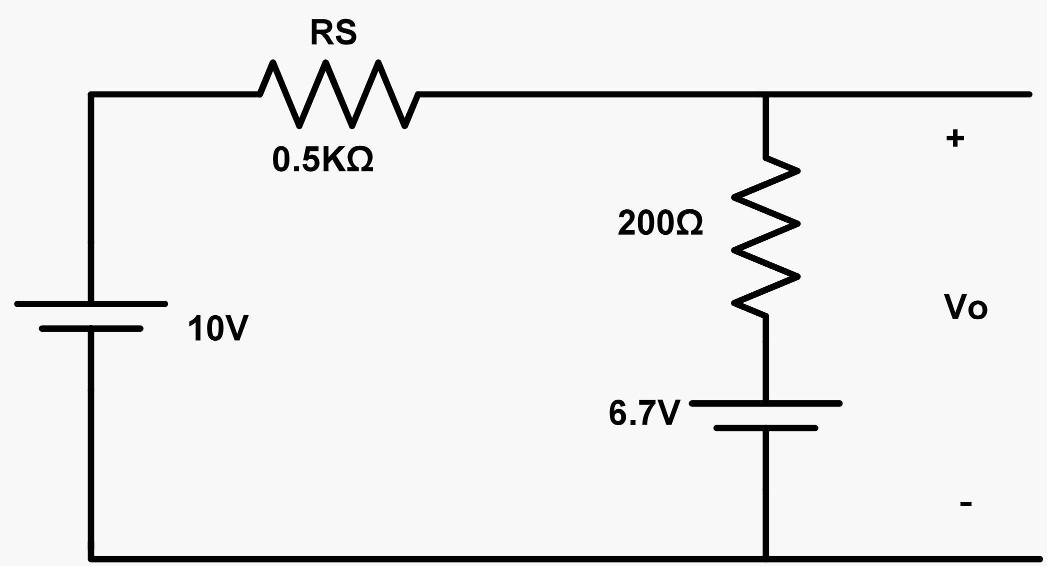
1) Let $R_L = \infty$

- Since $V_S > V_{ZO}$ $\therefore$ the zener is in breakdown

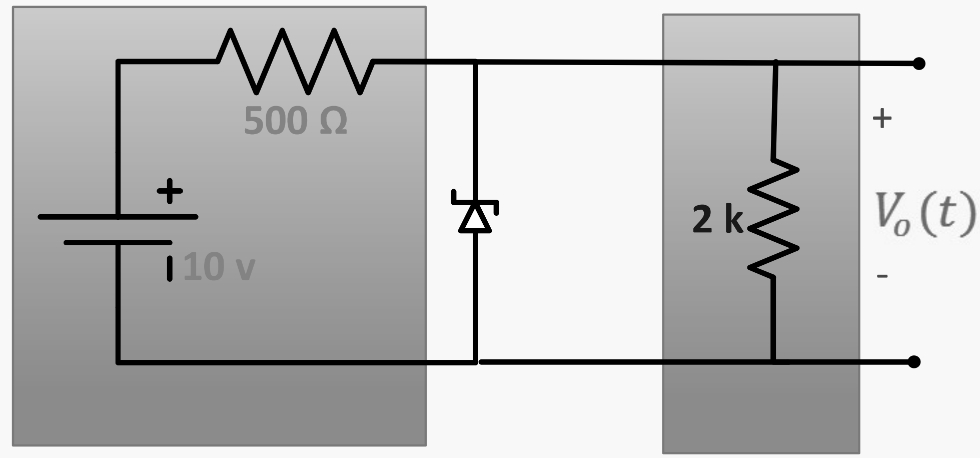
$V_O = 20\, I_Z + 6.7$

$I_Z = \frac{10-6.7}{520} = 6.35$ mA

$\therefore V_O = 6.83$ v



2) Let $R_L = 2K\Omega$

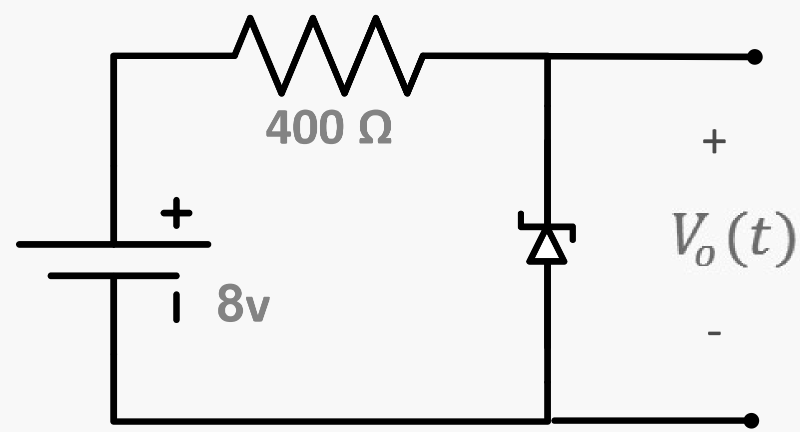


$V_{TH} = \frac{2000}{2000+500} \cdot 10 = 8v$

$R_{TH} = 500 \ \backslash\backslash \ 2000 = 400\ \Omega$

since $V_{TH} > V_{ZO}$; zener in breakdown

$V_O = r_z I_Z + V_{ZO}$



$V_O = 6.7 + 20\left(\frac{8-6.7}{420}\right) = 6.76v$

$I_L = \frac{V_O}{R_L} = I_L = \frac{6.76}{2K} = 3.38\ mA$

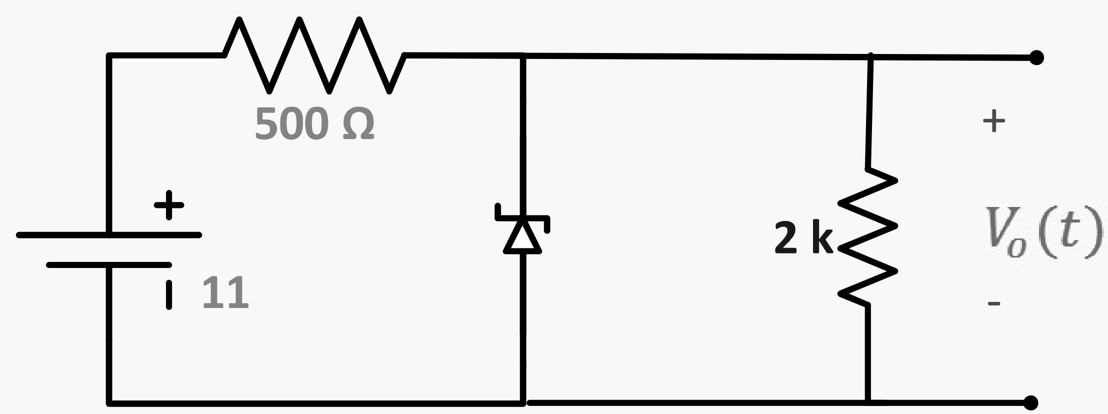
$\therefore \frac{\Delta V_O}{\Delta I_L} = \frac{6.76-6.83}{3.38-0} = -20.7\ mV/mA$

b) Line regulation = $\frac{\Delta V_O}{\Delta V_S}$

- $11v \geq V_S \geq 10v$

- When V_S = 10 v
  V_O = 6.76 v

- when V_S = 11 v



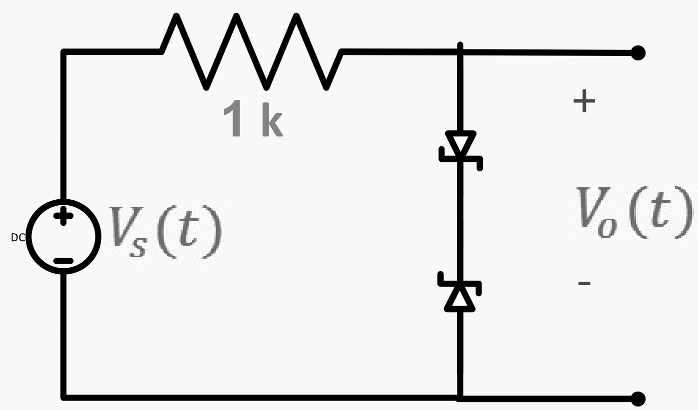
V_{TH} = 8.8v
R_{TH} = 0.4k Ω
$V_O = r_z I_Z + V_{ZO}$
$V_O = 6.7 + 20 \left(\frac{8.8-6.7}{420}\right) = 6.8$ v

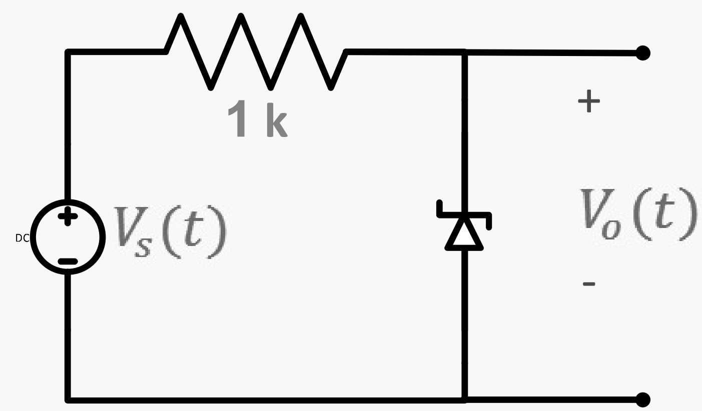
$I_L = \frac{V_O}{R_L} = I_L = \frac{6.76}{2K} = 3.38$ mA

$\therefore \frac{\Delta V_O}{\Delta V_S} = \frac{6.8-6.76}{11-10} = +38$ mV/V

For the following circuit ; calculate and sketch the output voltage for

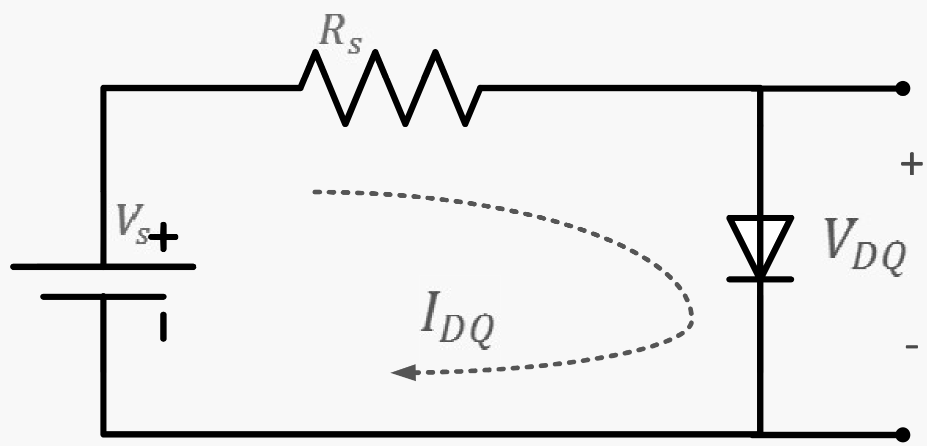
V_S(t) = 10sin ωt v
given V_Z = 5 v





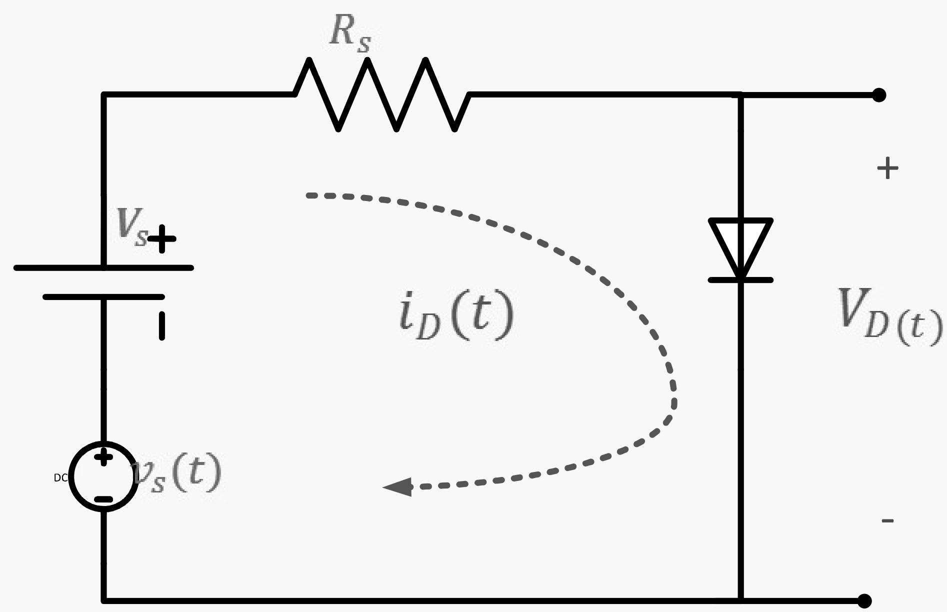
Ac Small Signal Analysis

- $I_{DQ} = I_S\left(e^{\frac{V_{DQ}}{\eta V_T}} - 1\right)$
- $I_{DQ} = I_S(e^{\frac{V_{DQ}}{\eta V_T}})$



now

- $i_D(t) = I_{DQ} + i_d(t)$
- $V_D(t) = V_{DQ} + v_d(t)$
- $i_D(t) = I_S\left(e^{\frac{V_D(t)}{\eta V_T}} - 1\right)$



- And since the diode is forward biased
- $i_D(t) = I_S(e^{\frac{V_D(t)}{\eta V_T}})$
- $i_D(t) = I_S(e^{\frac{V_{DQ} + v_d}{\eta V_T}})$
- $i_D(t) = I_S e^{\frac{V_{DQ}}{\eta V_T}} . e^{\frac{V_d}{\eta V_T}}$
- $i_D(t) = I_{DQ}(e^{\frac{v_d}{\eta V_T}})$
- using $e^x = 1+x$; x is very small

$$i_D(t) = I_{DQ}\,(1 + \frac{v_d(t)}{\eta V_T}) = I_{DQ+} \frac{v_d(t)}{\eta V_{T/I_{DQ}}}$$

but $i_D(t) = I_{DQ+}\, i_d(t)$

$\therefore i_d(t) = \frac{v_d(t)}{\eta V_{T/I_{DQ}}} = \frac{v_d}{r_d}$

where $r_d = \frac{\eta V_T}{I_{DQ}} = \frac{V_T}{I_{DQ}}$

$\therefore$ If V_S(t) = V_S+ vs(t)

V_S= Dc component

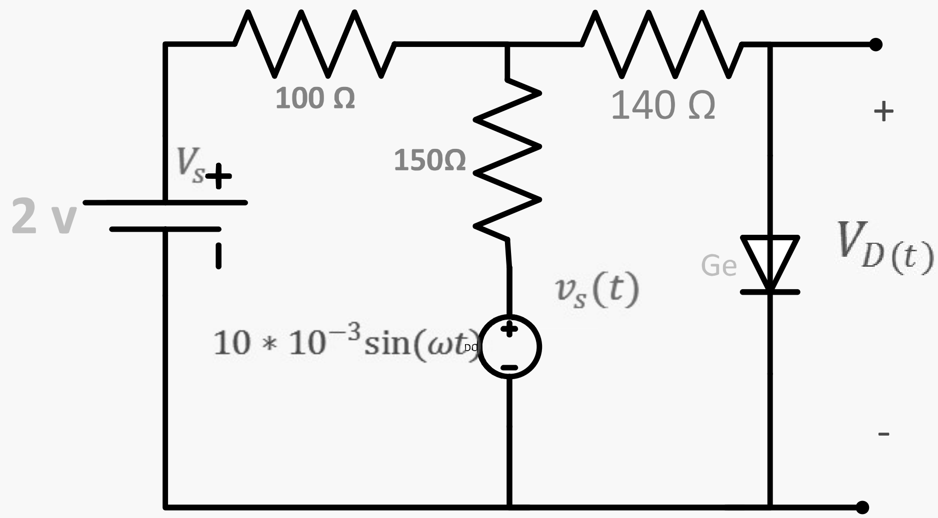
vs(t)= ac component

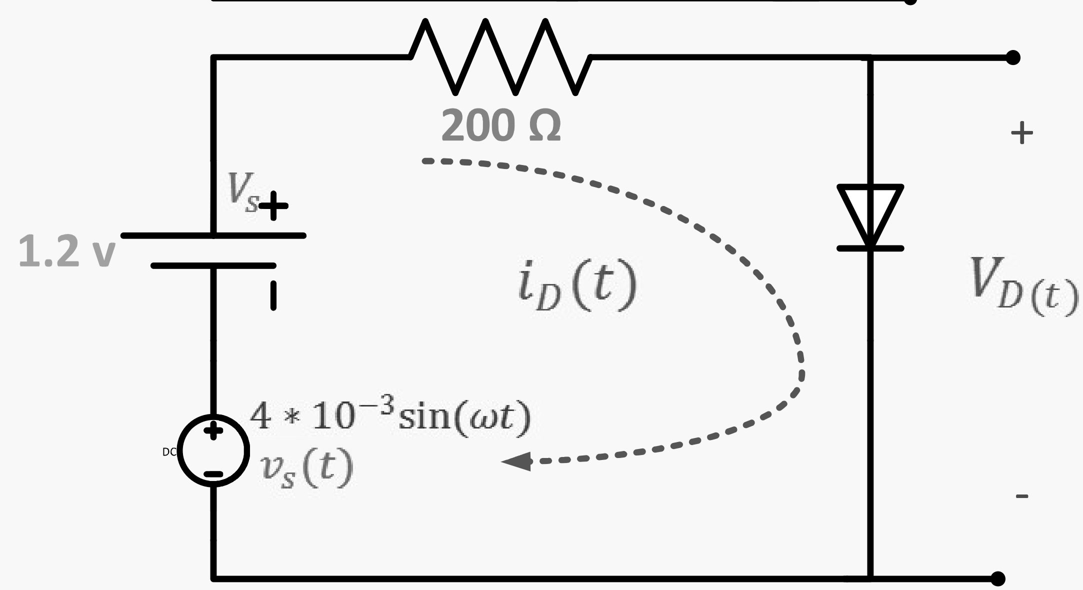
and the amplitude of vs(t) is small and the diode is always on ; we could use the superposition theorem to find the response ($V_{D(t)}$, $i_D(t)$) .

Example

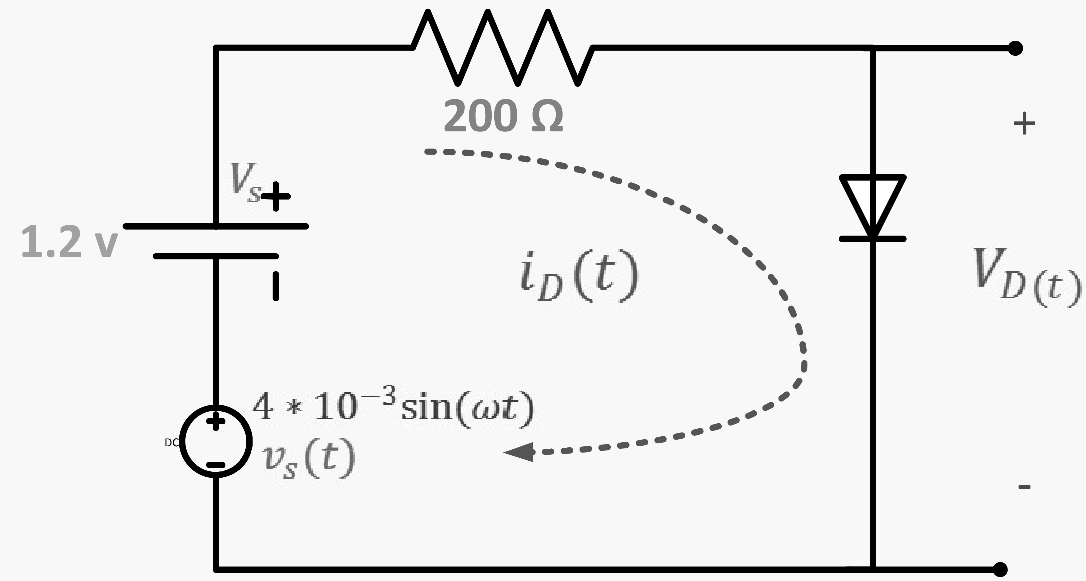
Find $V_D(t)$

Using Thevenin's Theorem

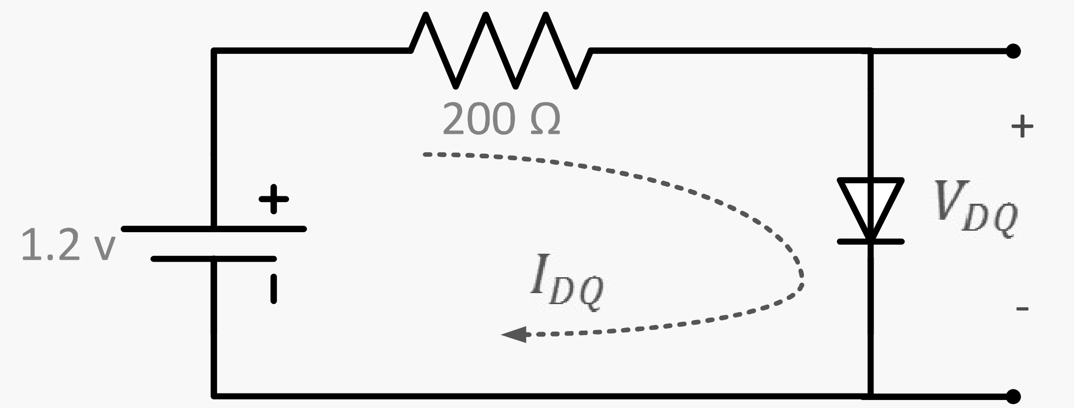




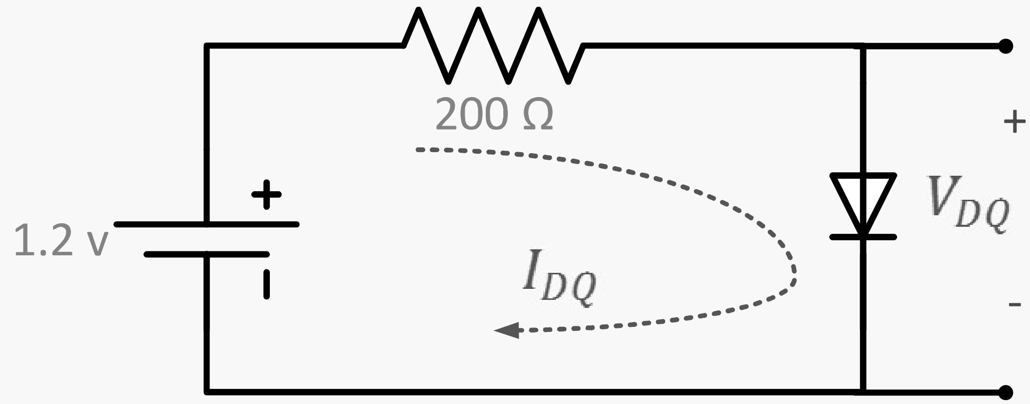
Since we have a dc source (1.2 v) and an ac signal ($4x10^{-3}$ sinωt v) and the diode is always on ; we use superposition theorem to find $V_D(t)$



1) to find V_{DQ} (DC Analysis)

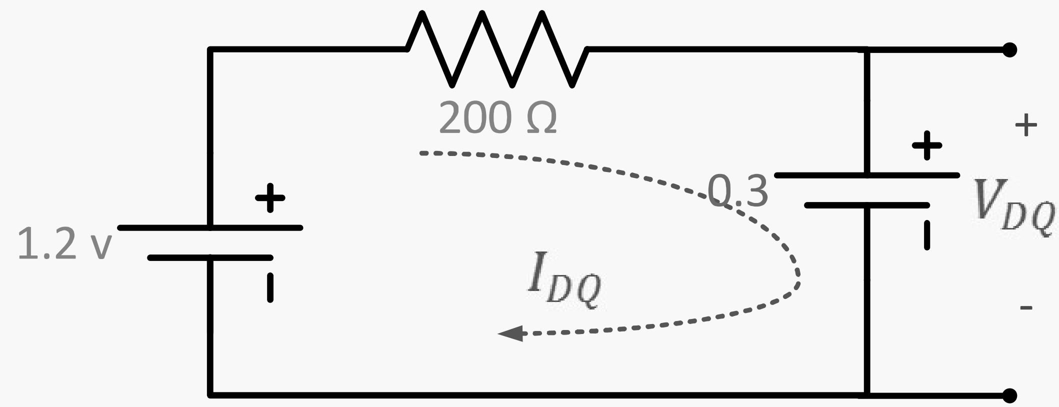


$\therefore V_{DQ}$ = 0.3 v



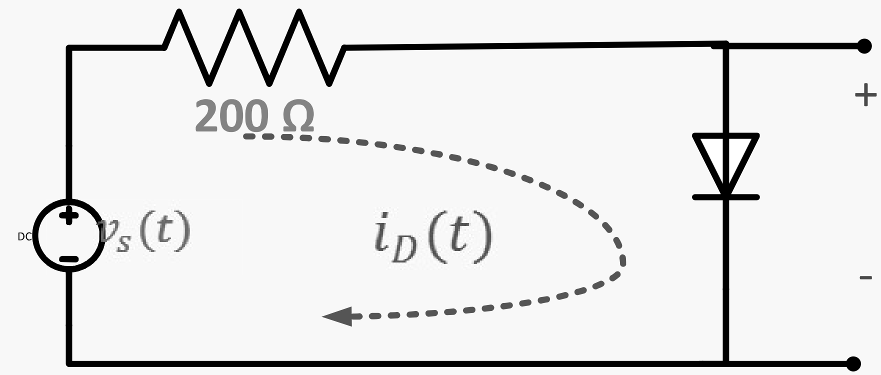
and $I_{DQ} = \frac{1.2v - 0.3v}{200}$ = 4.5 mA

$\therefore r_d = \frac{V_T}{I_{DQ}} = \frac{25.69mv}{4.5mA}$ = 5.69 Ω



2) To find $V_d(t)$ (ac small signal)

$v_d(t) = \frac{5.69}{200+5.69} \cdot 4 \times 10^{-3} \sin\omega t$ v



$v_d(t) = 0.1165 \times 10^{-3} \sin\omega t$ v

$\therefore V_D(t) = V_{DQ} + v_d(t)$

$V_D(t) = (0.3 + 0.1165 \times 10^{-3} \sin\omega t)$ v