pn Junction Diode

Introduction

- Simplest electronic device

- pn Junctions have many applications starting from simple DC converters to complex wave shaping circuits

- Diode are abundant in electronic devices

- Very important in designing power devices

- Depending on structure, many special purpose diodes can be designed e.g.: Zener diode, varactor diode, Gunn diode, tunnel diode, LED, Photo-voltaic cell

pn-Junction Formation

- The region where p-region and n-region meet is often called as metallurgical junction or simply junction
- These two regions form a pn-junction
- Free movable electrons are in the n-region, and movable holes in the p-region.
- n-region:
  – Dopant atom : pentavalent
  (Phosphorus, Arsenic)
  – Doping concentration N_D cm^{-3}
- p-region
  – Dopant atom: Trivalent
  (Boron)
  – Doping concentration N_A cm^{-3}

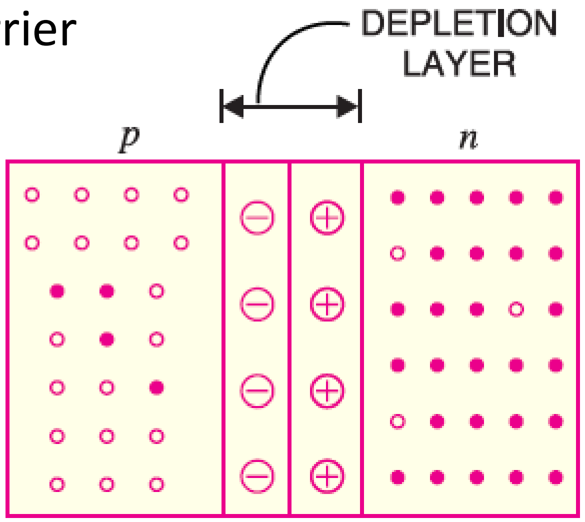
pn-junction: No electrical bias applied

- Diffusion effects – The holes and electrons move from area of high concentration to areas of low concentration.

- Holes & electrons annihilate each other to form an area depleted of free charge. This is known as the depletion region and blocks any further flow of charge carriers across the junction

- There exists a potential difference across the depletion layer and is called barrier potential (V_0)

- For silicon, V_0 = 0.7 V ; For germanium, V_0 = 0.3 V



pn-junction: No electrical bias applied

- On p-side from the vicinity of metallurgical junction mobile holes diffuse to n-side leaving behind negatively charged immobile ions.
- On n-side from the vicinity of metallurgical junction mobile electrons diffuse to p-side leaving behind positively charged immobile ions.
- This loss of electrons from the n-type material leaves the surface layer positively charged.
- Similarly, the p-type material will have a negatively charged surface layer.
- Thus, an electric field is established which opposes the diffusion of electrons when the Fermi levels are equal (dynamic equilibrium is established)

The built-in potential (ϕ_j, V_{bi}) is given by

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

pn-junction: No electrical bias applied

On p-side

• Holes are majority carriers
N_A cm^{-3}

• Electrons are minority carriers
$n_p = n_i^2/N_A$ cm^{-3}

• Negatively charged immobile dopant ions ($-qN_A$ cm^{-3})

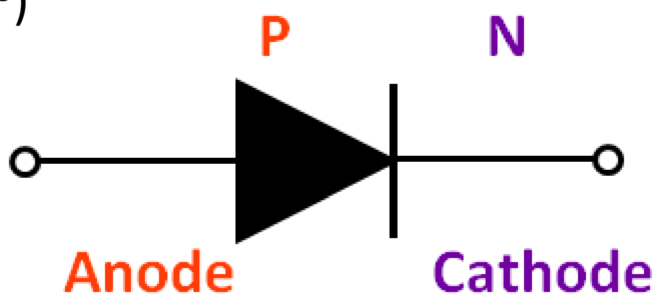
On n-side

• Electrons are majority carriers
N_D cm^{-3}

• Holes are minority carriers
$p_n = n_i^2/N_D$ cm^{-3}

• Positively charged immobile dopant ions (qN_D cm^{-3})

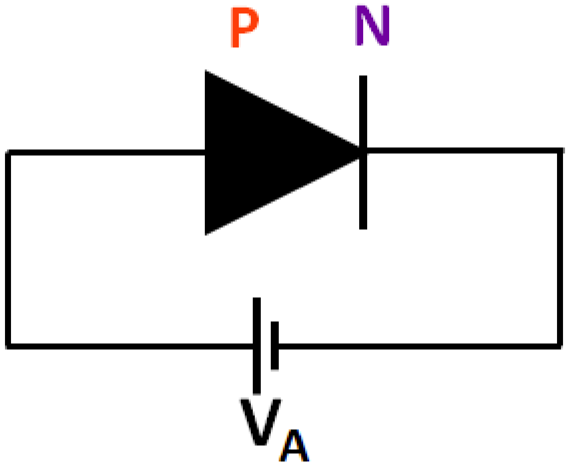
As this got two electrodes, this is termed as **DIODE**

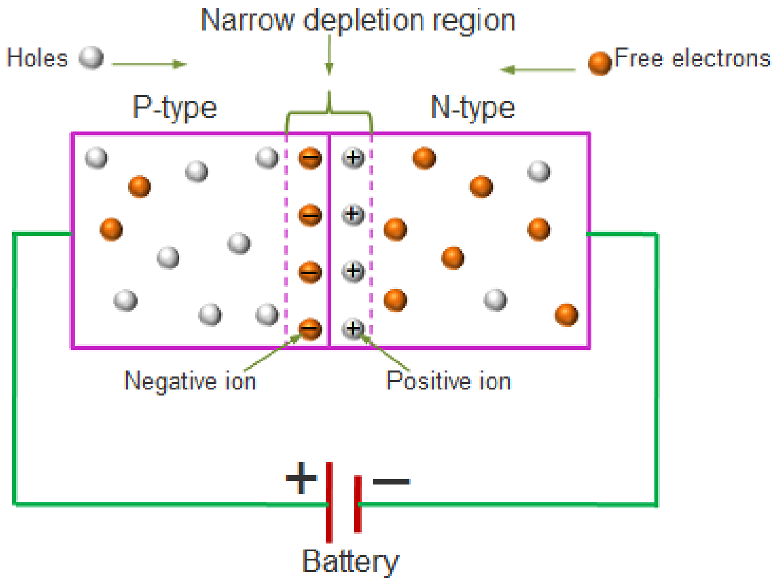


Circuit symbol

pn Junction: Forward Bias

- pn junction is biased such that depletion layer width decreases
- p-type is connected to positive
- n-type is connected to ground or negative of supply
- V_A is treated as positive in forward bias
- Due to forward bias electrons from n-region and holes from p-region are forced into depletion region
- depletion layer to decrease
- probability of current conduction increases
- Once the difficulty of getting through the depletion region has been overcome, current can rise with applied voltage (Ohm's law)





Forward bias

pn-junction: Forward Bias

Current Voltage Relationship:

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

Where, I_D– Current through Diode

I_S– Reverse Saturation Current

V_D– Voltage drop across diode

V_T– Thermal Voltage

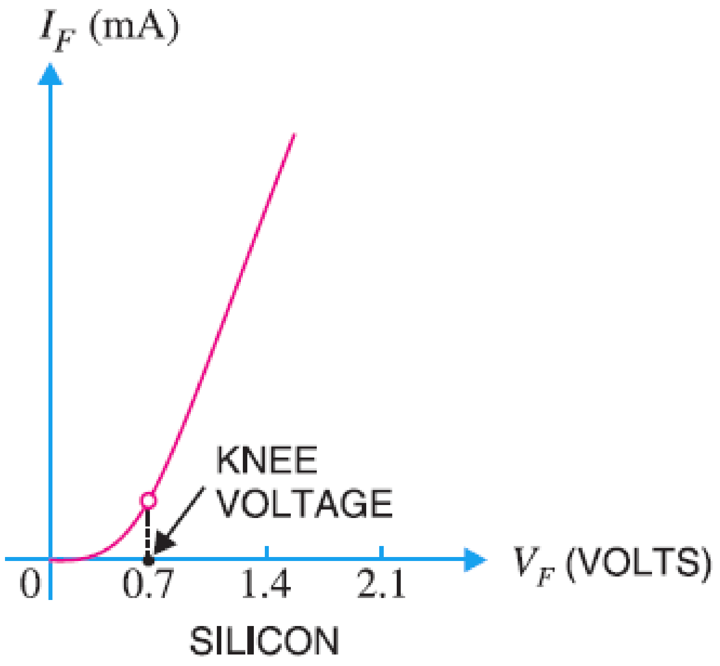
$$V_T = \frac{kT}{q}$$

k– Boltzmann's Constant

T– Absolute Temperature

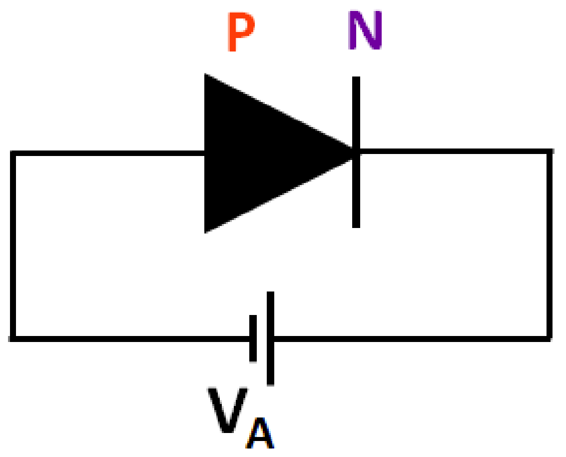
q– Electronic Charge

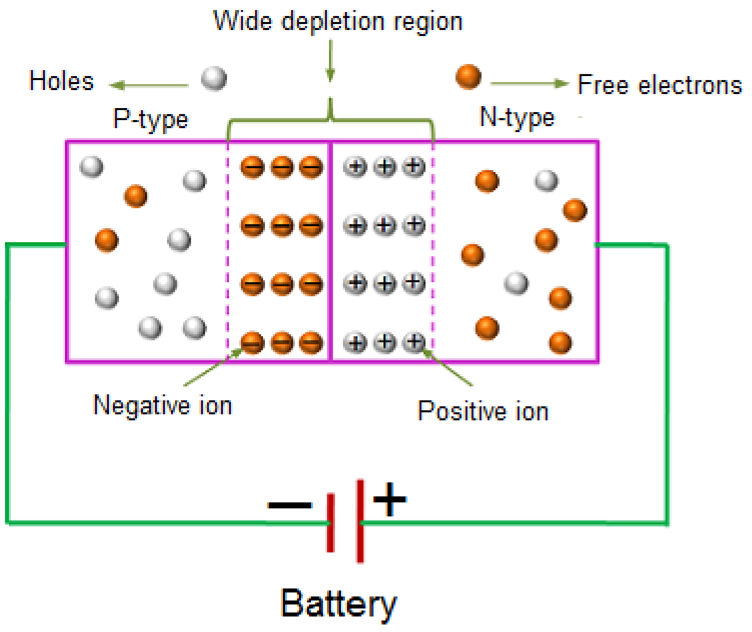
n – ideality factor, a number between 1 and 2



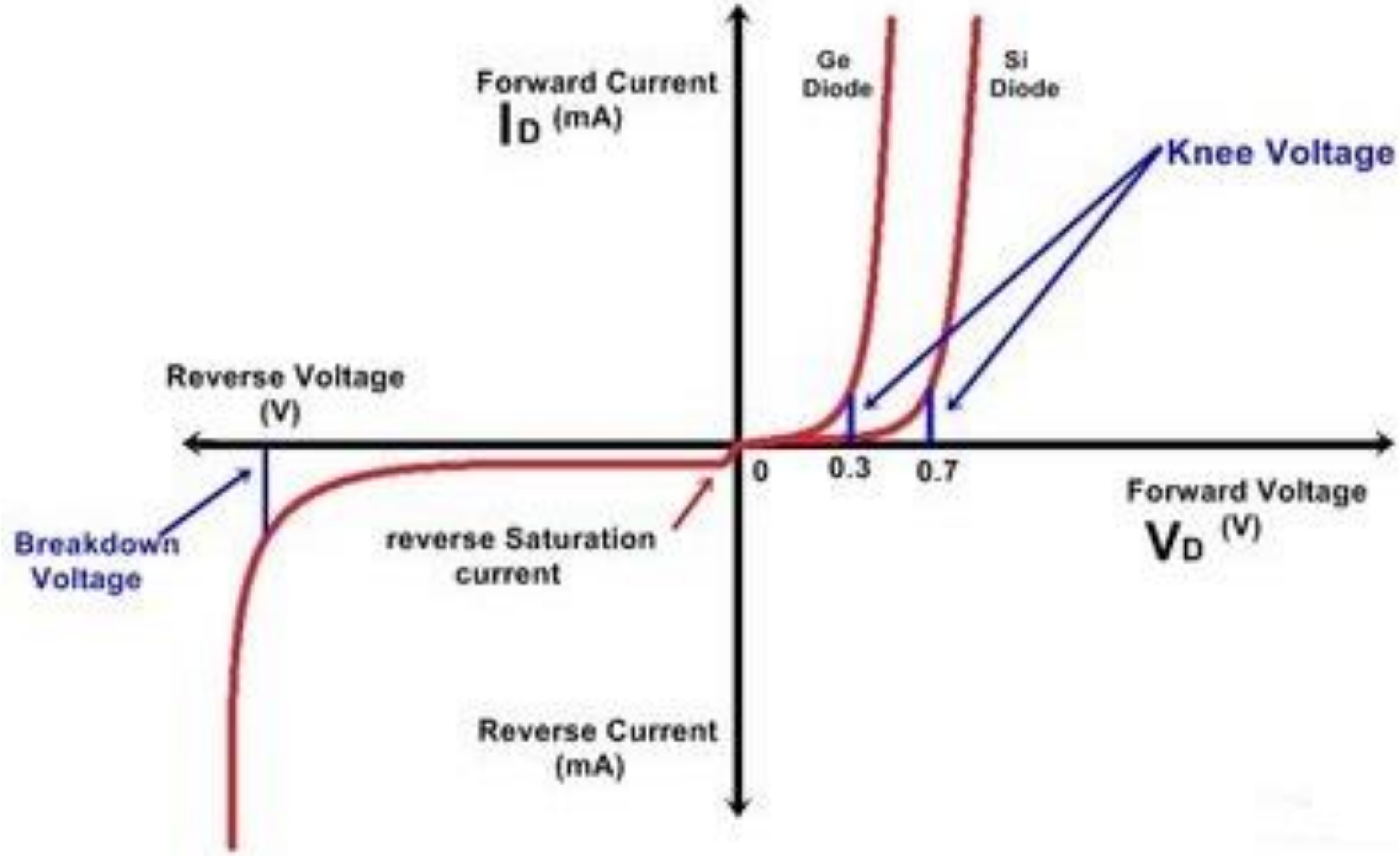
pn-junction: Reverse Bias

- PN junction is biased such that depletion layer width increases
- p-type is connected to negative and n-type to ground or positive of supply
- V_A is treated as negative in reverse bias
- Depletion region width grows, carriers find it more and more difficult to get through the barrier
- Little current flows because barrier too high
- Increasing voltage further → high electric field
- Depletion region eventually breaks down
- Reverse saturation current flows





Reverse bias



P-N Junction Diode V-I Characteristics

pn-junction: VI Characteristic

- **Knee Voltage:** This is the minimum required voltage to start the conduction of current through diode. This is also known as **cut-in voltage**. This is the forward voltage at which the diode current starts increasing rapidly. The knee voltage of Si diode is 0.7 V and 0.3 V of Ge diode.

- **Breakdown Voltage:** It is the minimum Amount of reverse bias voltage at which diode starts conduction in reverse bias connection. This breakdown characteristics of diode is used in Zener Diode which is always used in reverse bias and limits the circuit voltage.

- **Reverse Saturation Current:** On both sides of p-n junction, a very small amount of minority charge carriers are present. Due to this, a small amount of current flows through the diode in reverse bias condition. This current does not change with applied bias voltage and is called reverse saturation current.

Important Formulas

$$\sigma = q(n\mu_n + p\mu_p) \qquad \rho = \frac{1}{\sigma}$$

Energy gap of Silicon is 1.1 eV and Germanium is 0.7 eV

$$np = n_i^2 \qquad n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$$

$$E_C - E_i = \frac{E_G}{2} = E_i - E_V$$

$$n = n_i e^{\frac{(E_F - E_I)}{kT}} \qquad p = p_i e^{\frac{(E_i - E_F)}{kT}} \qquad V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) \qquad \frac{kT}{q} = 26\text{mV}$$

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

When n=1 and as $I_S \ll I_D$

Diode Circuits

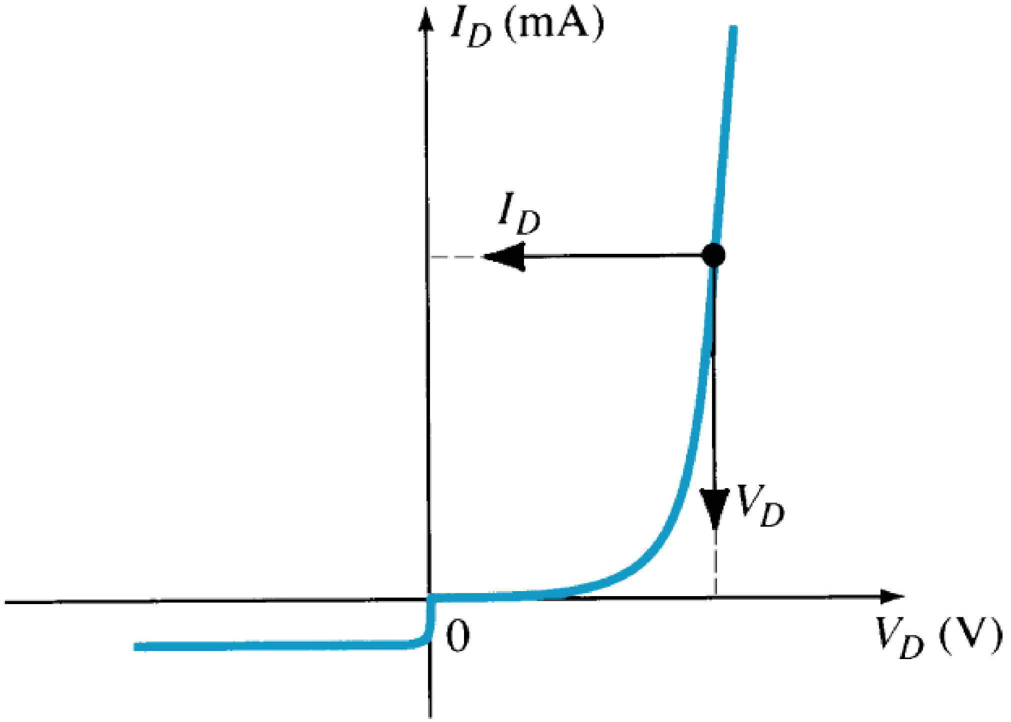
Resistances in Diodes

- There are mainly two types of resistance
  - DC (static) resistance
  - AC (dynamic) resistance

DC (Static) Resistance

- For a specific applied DC voltage (V_D) the diode has a specific current (I_D) and a specific resistance (R_D).

$$R_D = \frac{V_D}{I_D}$$



AC (Dynamic) Resistance

- The resistance depends on the amount of current (I_D) in the diode.

$$\frac{1}{r_D} = \frac{\partial I_D}{\partial V_D}$$

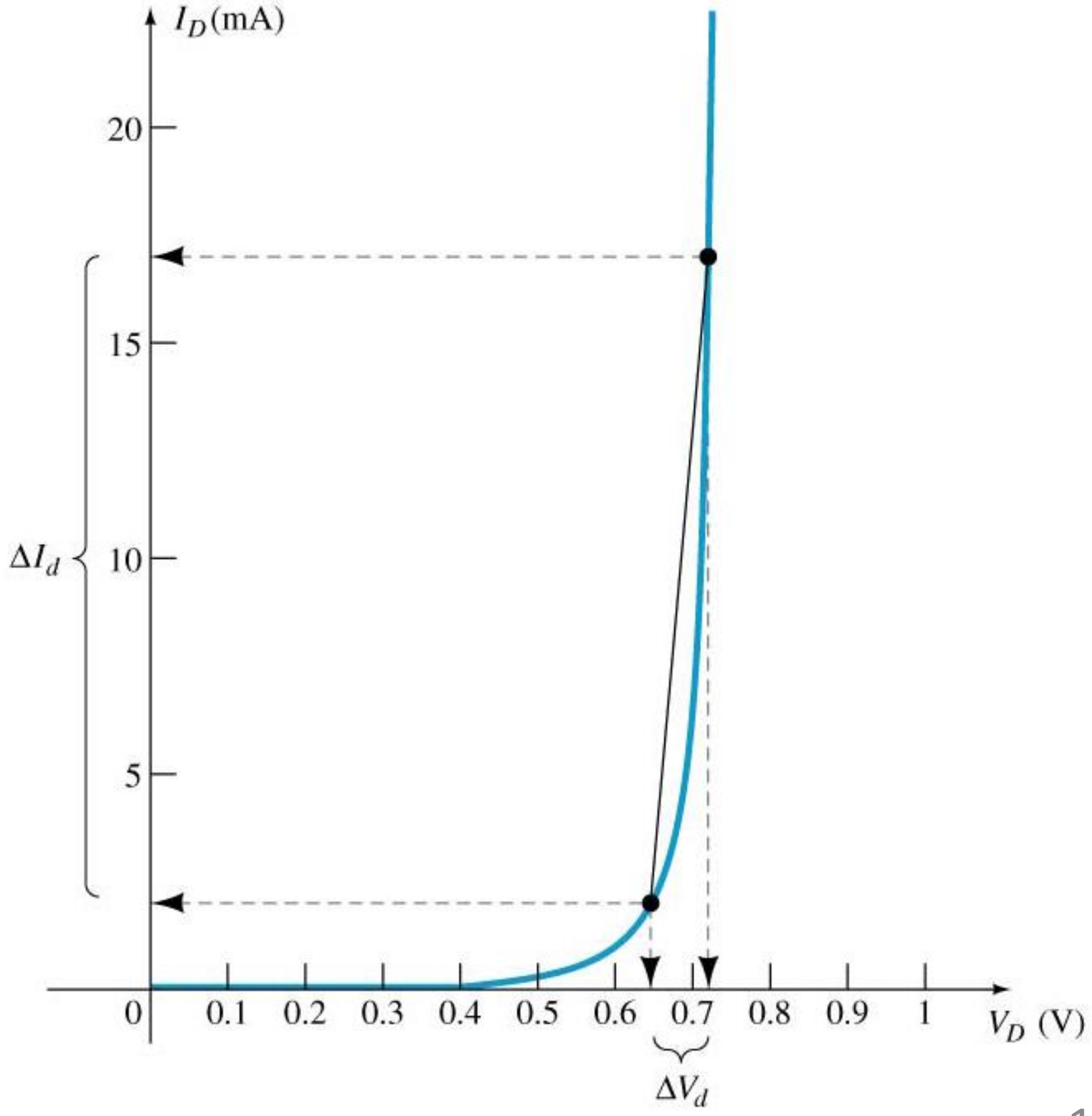
- The voltage across the diode is relatively constant and V_T = 26 mV at T = 300K.

$$r_D = \frac{V_T}{I_D} = \frac{26mV}{I_D} \quad \text{at T=300 K}$$

- In the reverse bias region: the resistance is effectively infinite. The diode acts like an open.

AC (Dynamic) Resistance

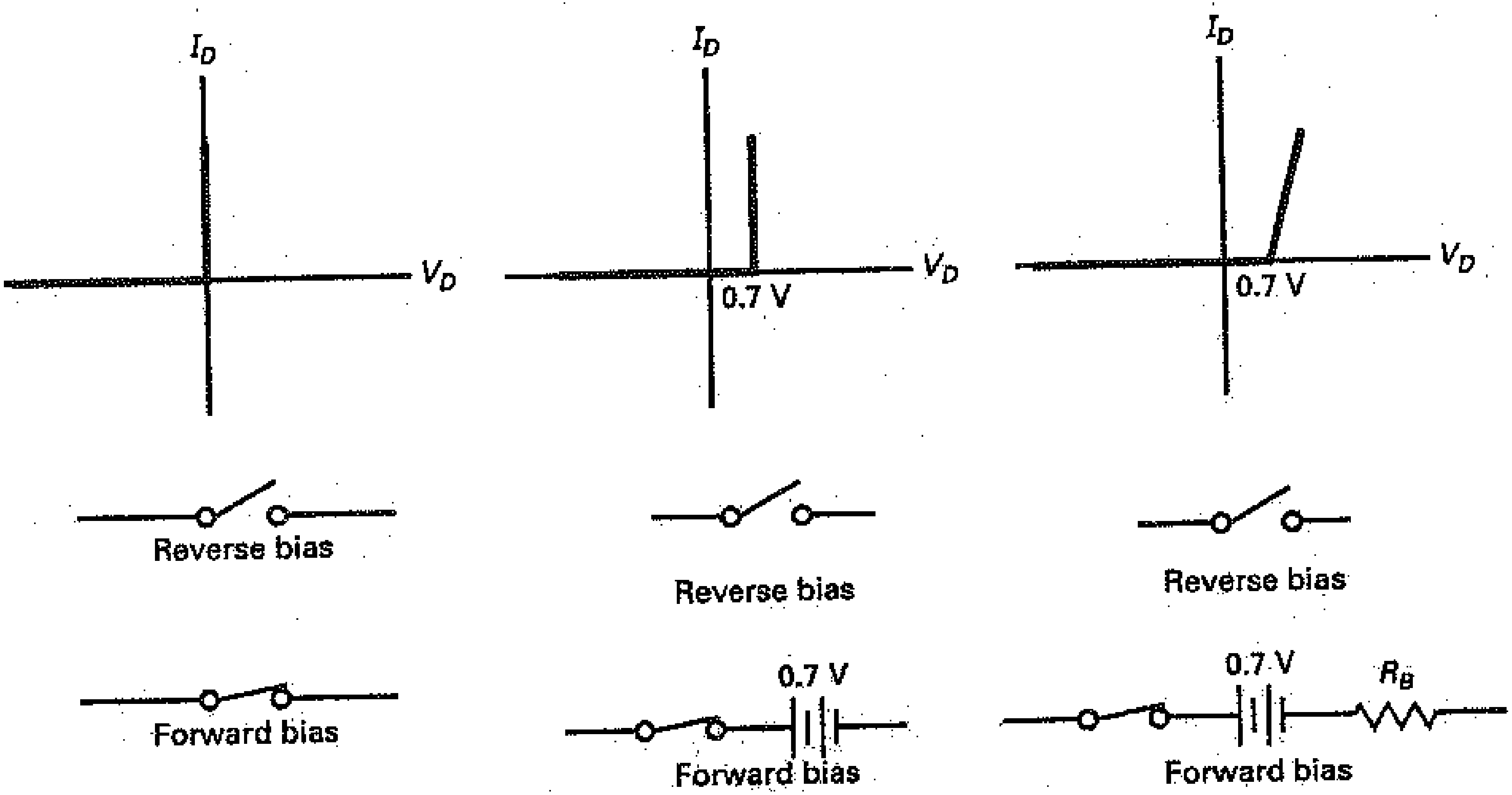
AC resistance can be calculated using the current and voltage values for two points on the diode characteristic curve.



Diode Equivalent Circuit

Diode curve

Equivalent circuit

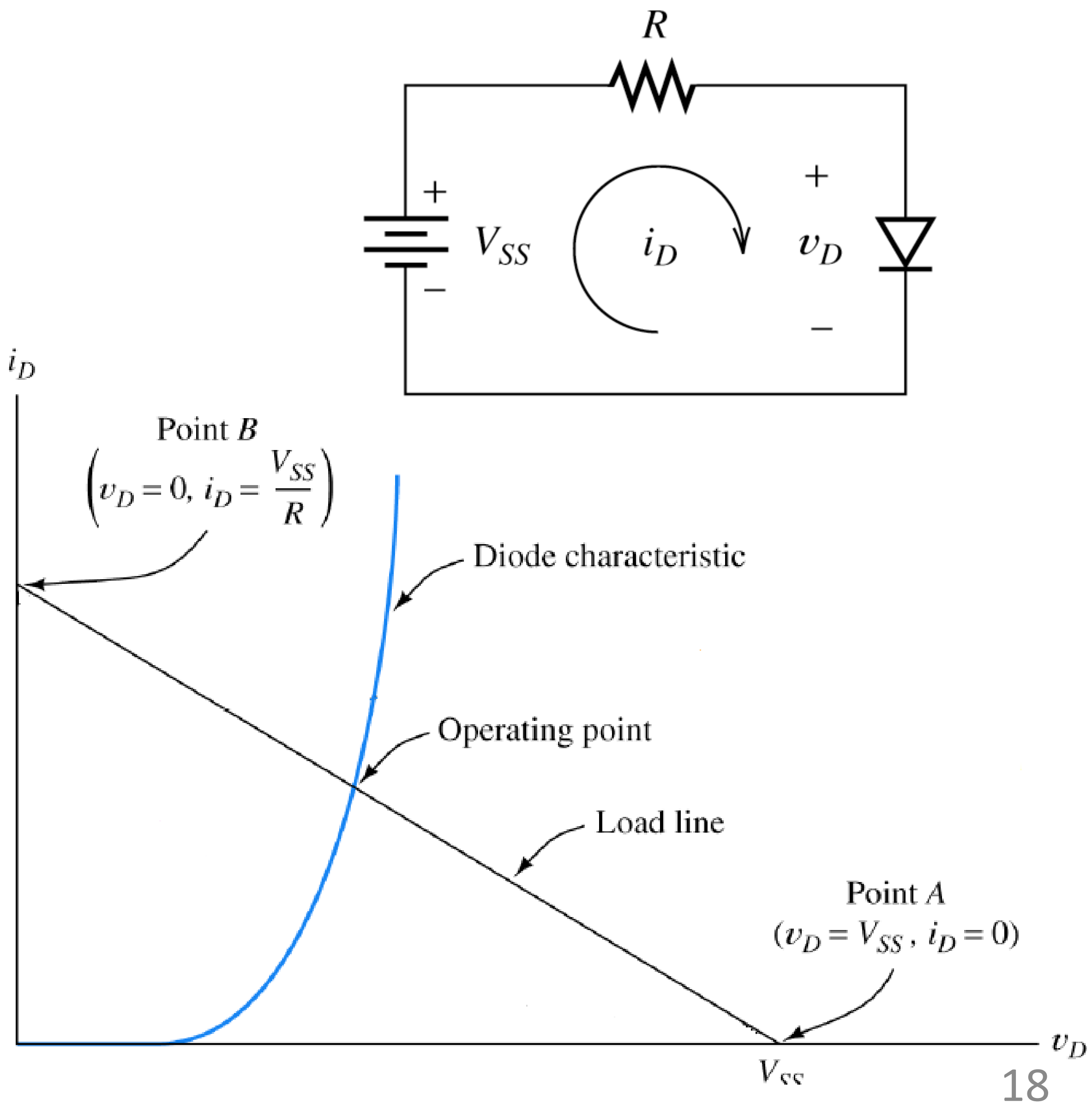


Load Line Analysis

Consider the diode circuit

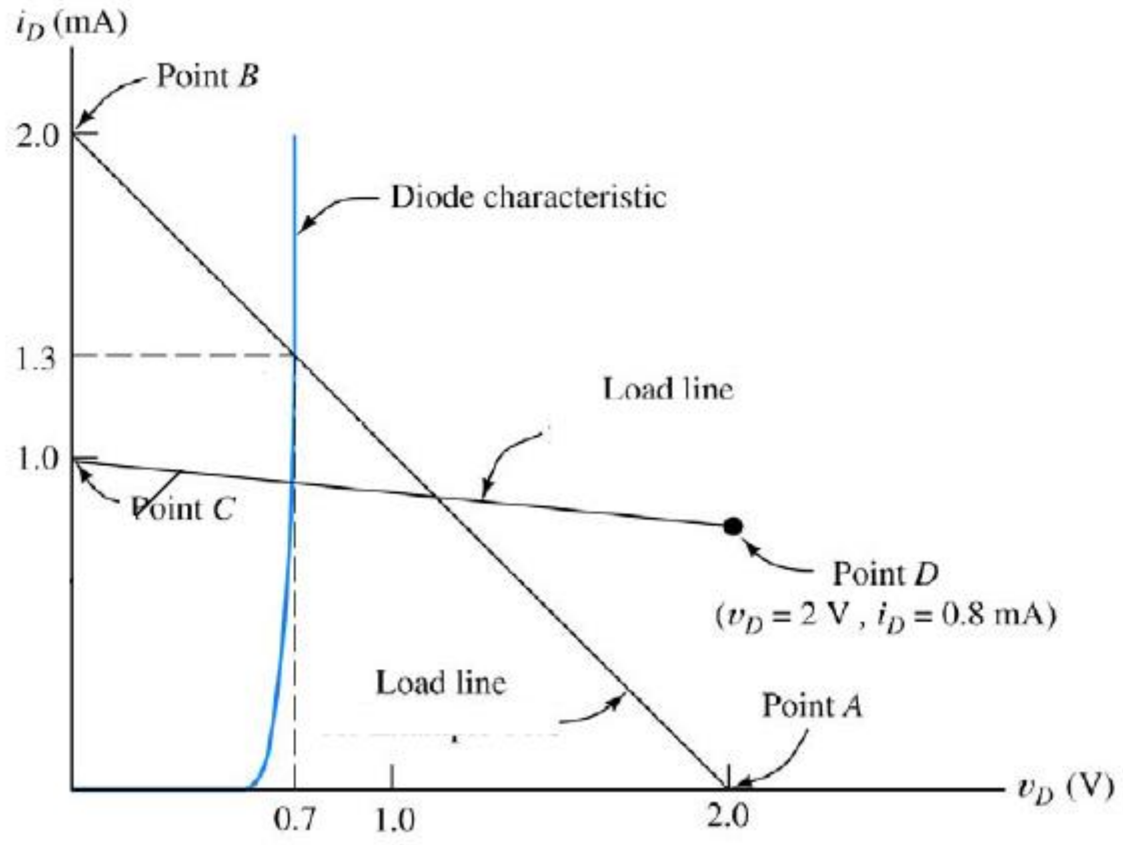
$$V_{ss} = Ri_D + v_D$$

The load line, usually a straight line, represents the response of the linear part of the circuit, connected to the nonlinear device in question. The points where the characteristic curve and the load line intersect are the possible operating point(s) (Q points) of the circuit; at these points the current and voltage parameters of both parts of the circuit match.



Problem 1: The circuit shown below has Vss=2V and R =1 kΩ. Diode with characteristics are as shown, Find the diode voltage and current at the operating point

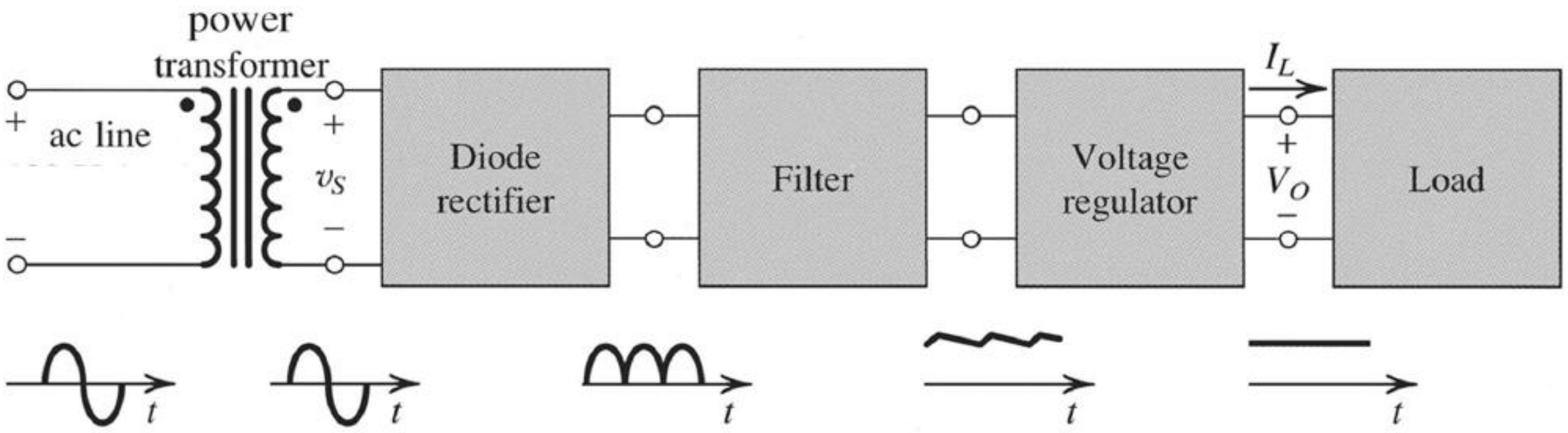
$\mathbf{V_{DQ}=0.7V}$ **and** $\mathbf{i_{DQ} = 1.3mA}$



Rectifier Circuits

AC to DC Voltage Conversion: Block Diagram

- All electronic circuits require a dc bias, which requires a power supply.
- The first stage of a dc power supply is formed by diode rectifier
- Rectification is the process of converting an alternating (ac) voltage into one that is limited to one polarity.
- Rectification is classified as half-wave or full-wave rectifier.



Half Wave Rectifier Circuits

- Half wave rectifier circuit is shown in figure

- The circuit contains one diode (D_1) and one load resistor (R_L) connected in series to an ac signal (v_i),

  $$v_i = V_o \sin(\omega t)$$

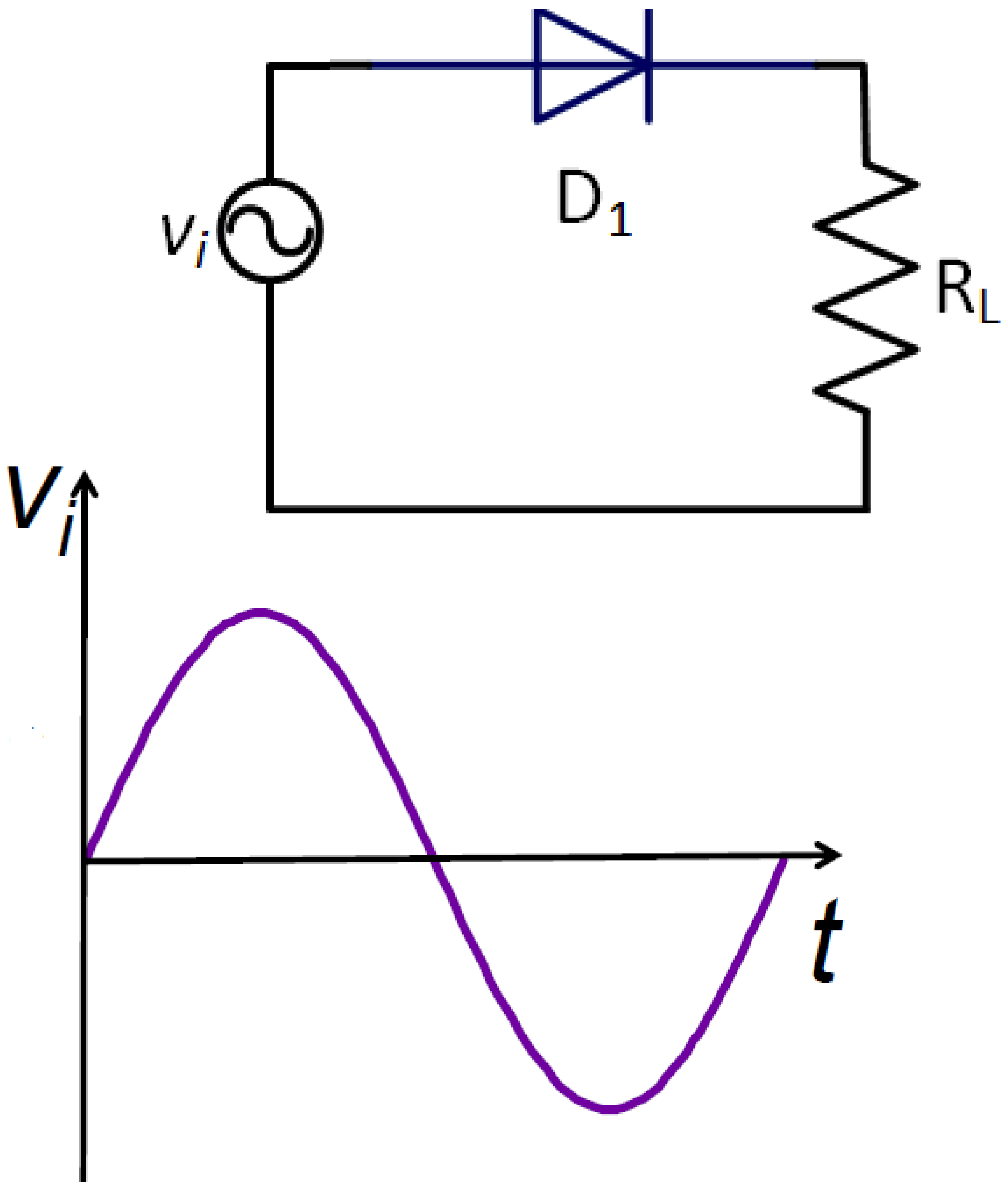
- Applying KVL,

  $$v_i = V_D + v_0$$

- Here, v_o is the output voltage across the load resistor R_L.

  $$v_0 = i_D R_L$$

  $$i_D = \frac{v_i - V_D}{R_L}$$



Half Wave Rectifier Circuits

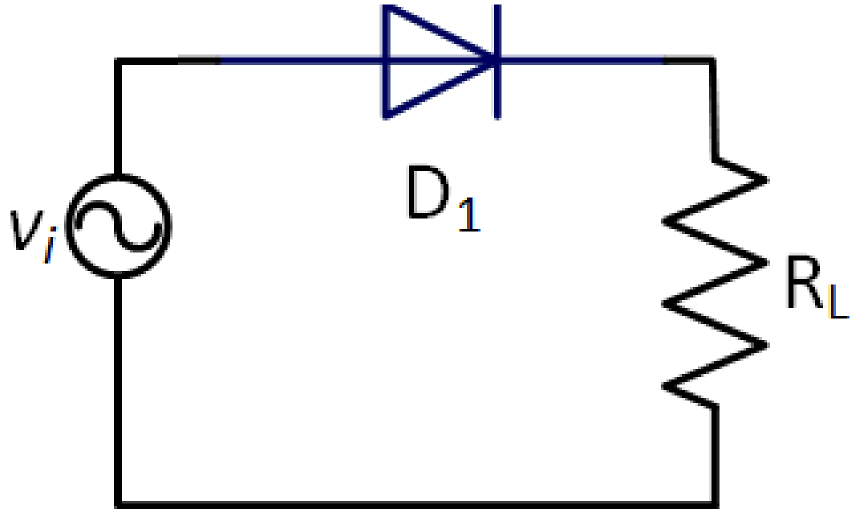
- In the positive half cycle,

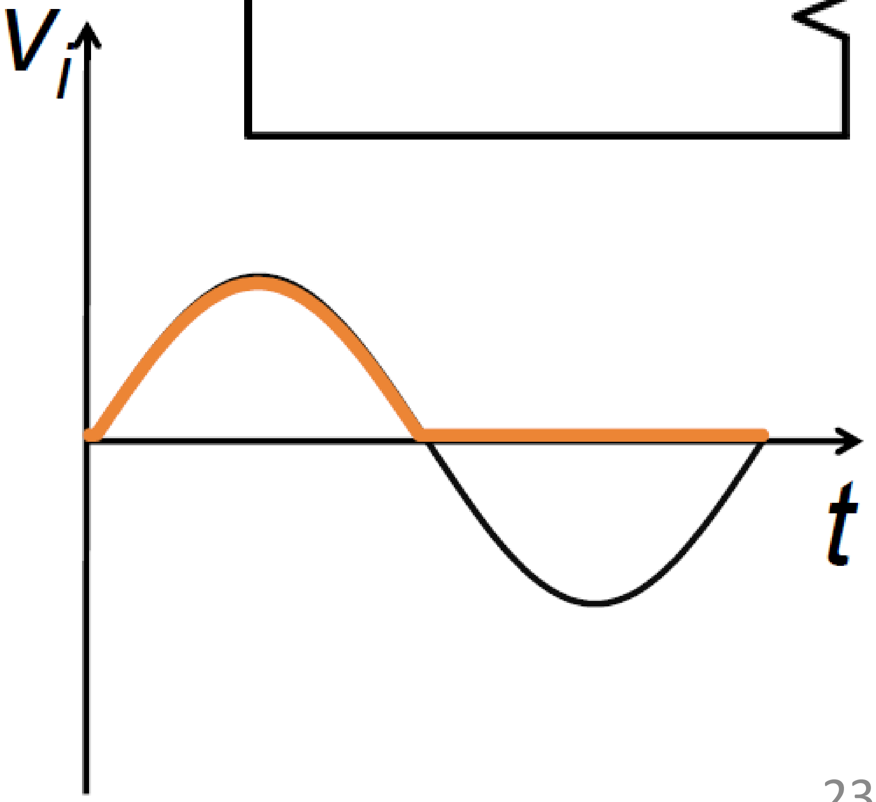
  When v_i<V_D, the diode D_1 is off

– entire input voltage drops across the diode
– current through the circuit $I_D = 0$
– output voltage (v_o, voltage across R_L) is 0
– no voltage across the load resistor

When v_i>V_D, the diode D_1 is on,

– voltage across the diode remains constant (= V_D)
– Current through the circuit flows and $I_D \neq 0$
– output voltage (v_o, voltage across R_L) starts to raise
– v_o reaches its maximum value when v_i reaches its maximum value
– v_o follows v_i .

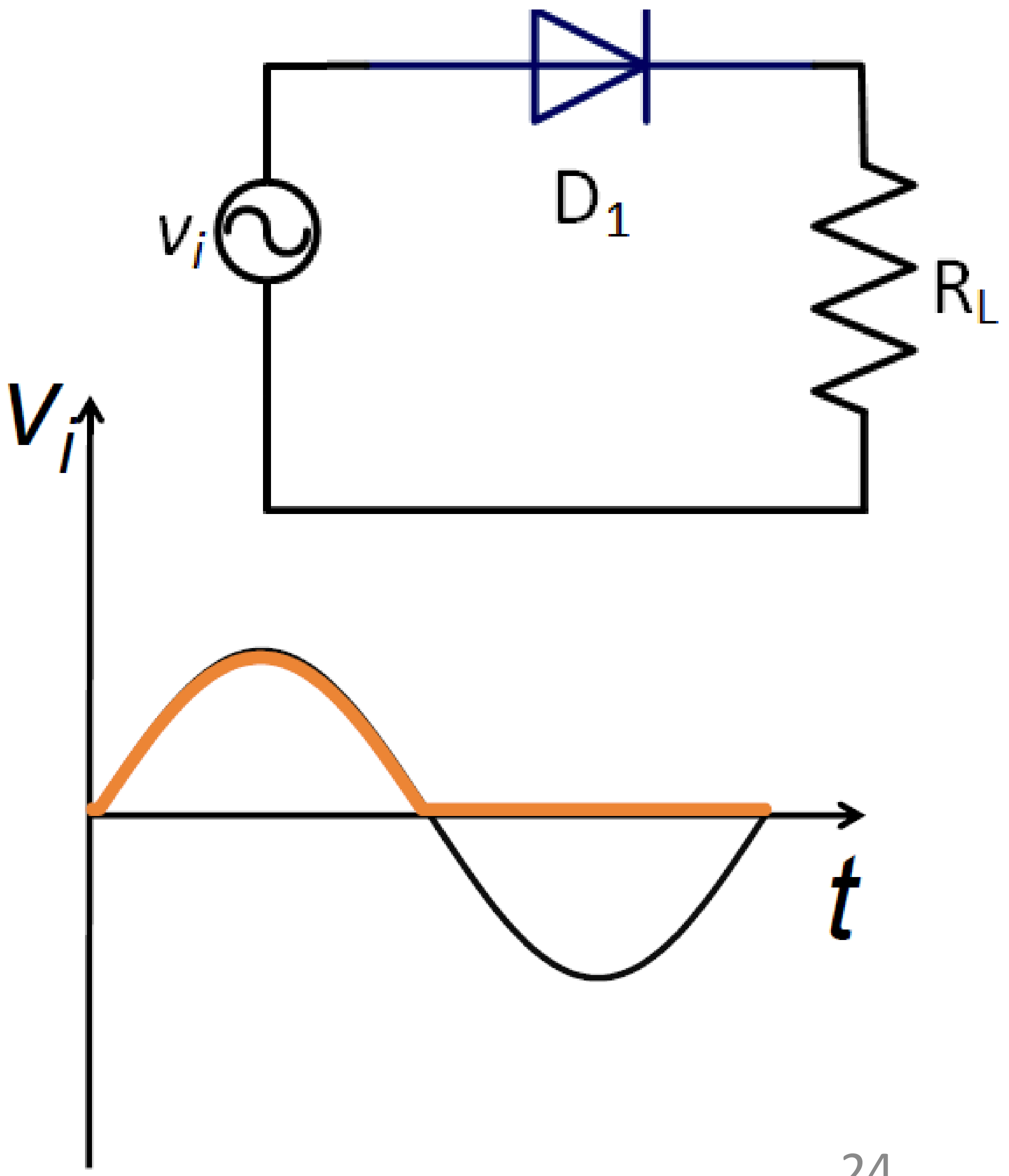




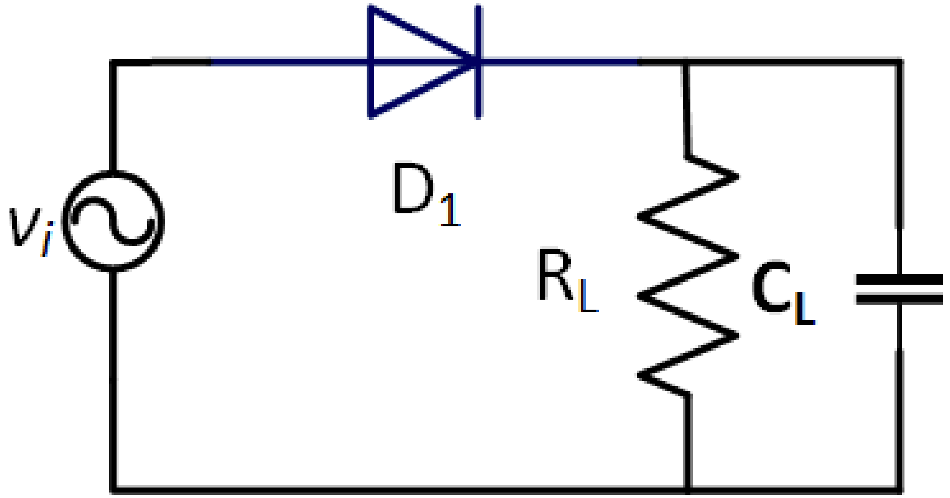
Half Wave Rectifier Circuits

- In the negative half cycle,
  The diode D_1 is reverse biased

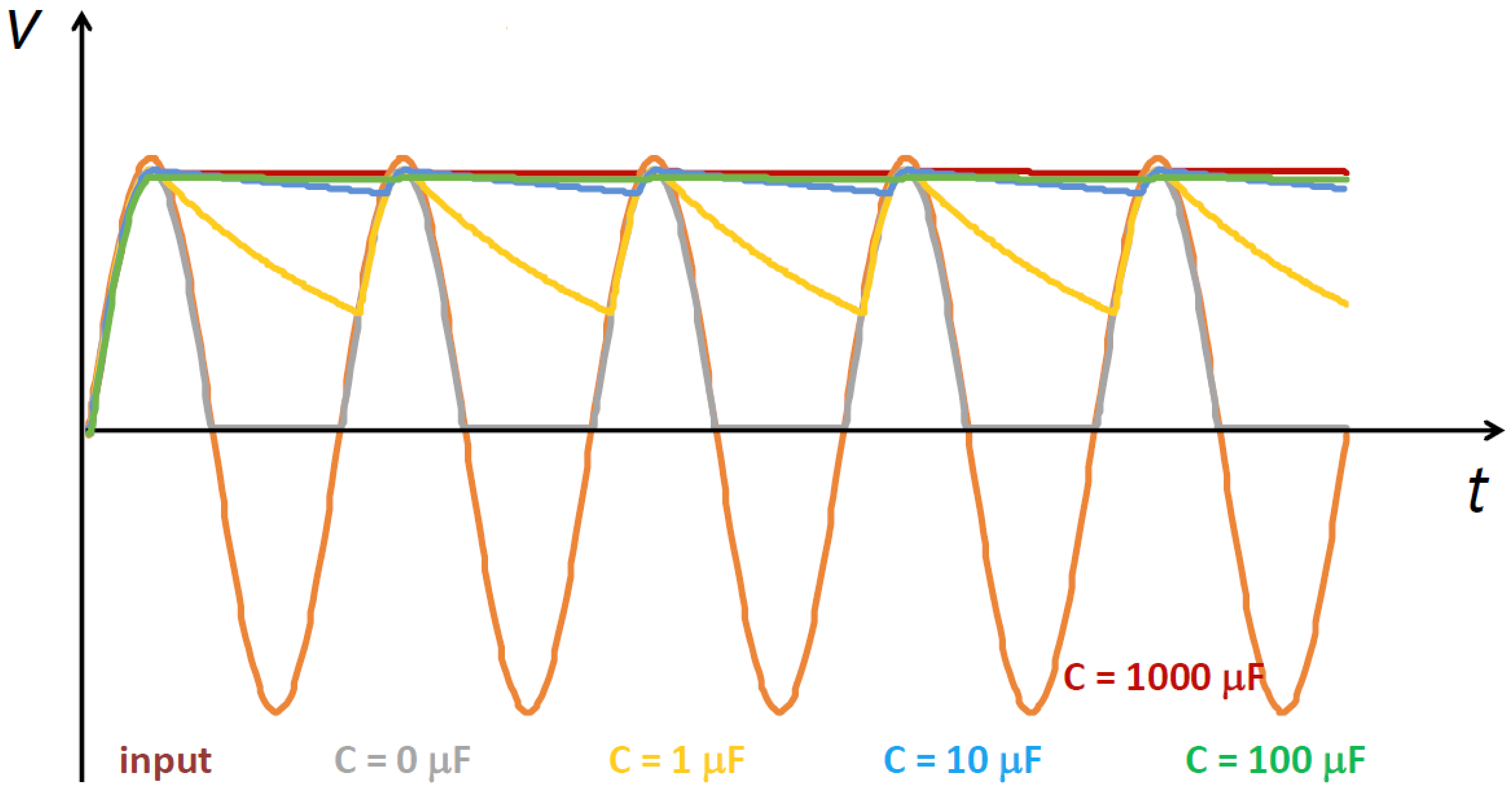
– Diode is in cut-off mode
– entire input voltage drops across the diode
– current through the circuit $I_D = 0$
– output voltage (v_o, voltage across R_L) is 0
– no voltage across the load resistor



Half Wave Rectifier Circuits



- Output is taken across a RC-filter
- A capacitor C_L is added in parallel to R_L.
- When the diode D_1 is conducting (say during the positive half cycle of the input signal), the capacitor C_L charges to a value v_0.
- When the diode D_1 is not conducting (say during the negative half cycle of the input signal), the capacitor C_L discharges through R_L.
- R_L determines the current through the circuit
- Value of ripple depends on C_L
- To have a fairly smooth ripple, the time constant (τ) of the filter is chosen such that $\tau = R_L C_L = 5T$
  where T is the time period of the input signal

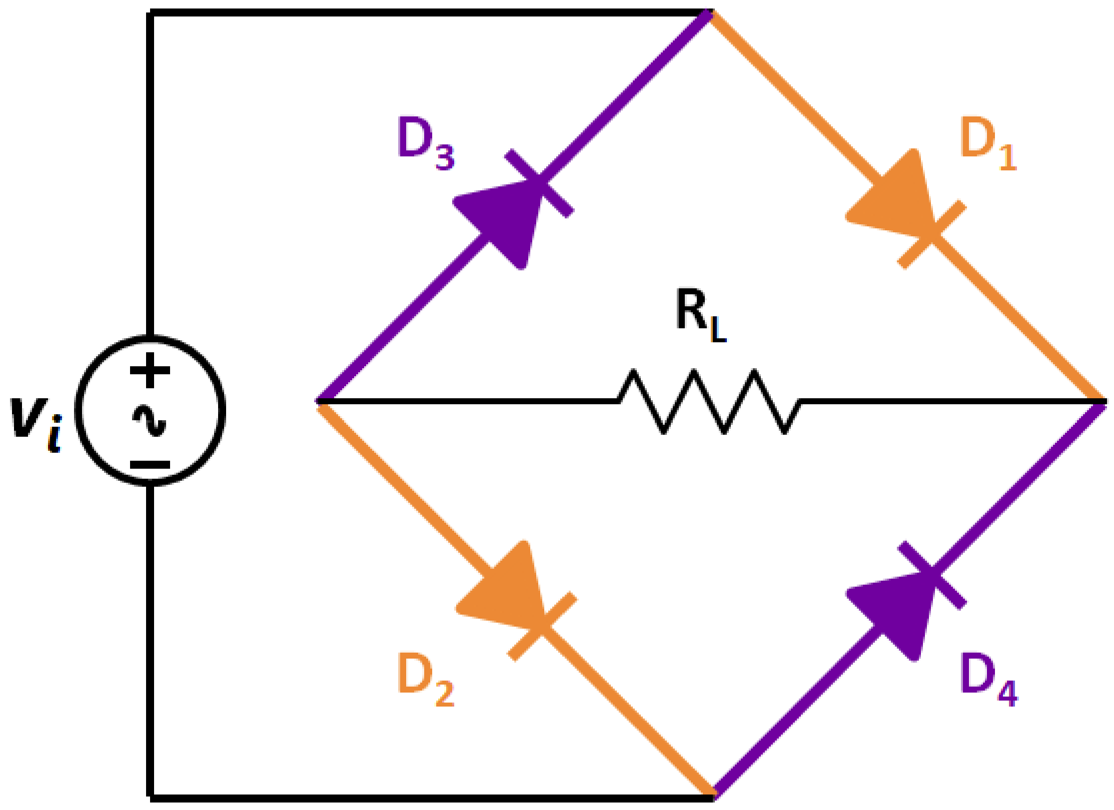

V
t
C = 1000 μF
input
C = 0 μF
C = 1 μF
C = 10 μF
C = 100 μF

Full Wave Rectifier Circuits

- Full wave rectifier circuit is shown in figure

- The circuit contains four diodes (D_1, D_2, D_3 and D4) and one load resistor (R_L) connected in series to an ac signal (v_i),

$$v_i = V_o \sin(\omega t)$$



Full Wave Rectifier Circuits

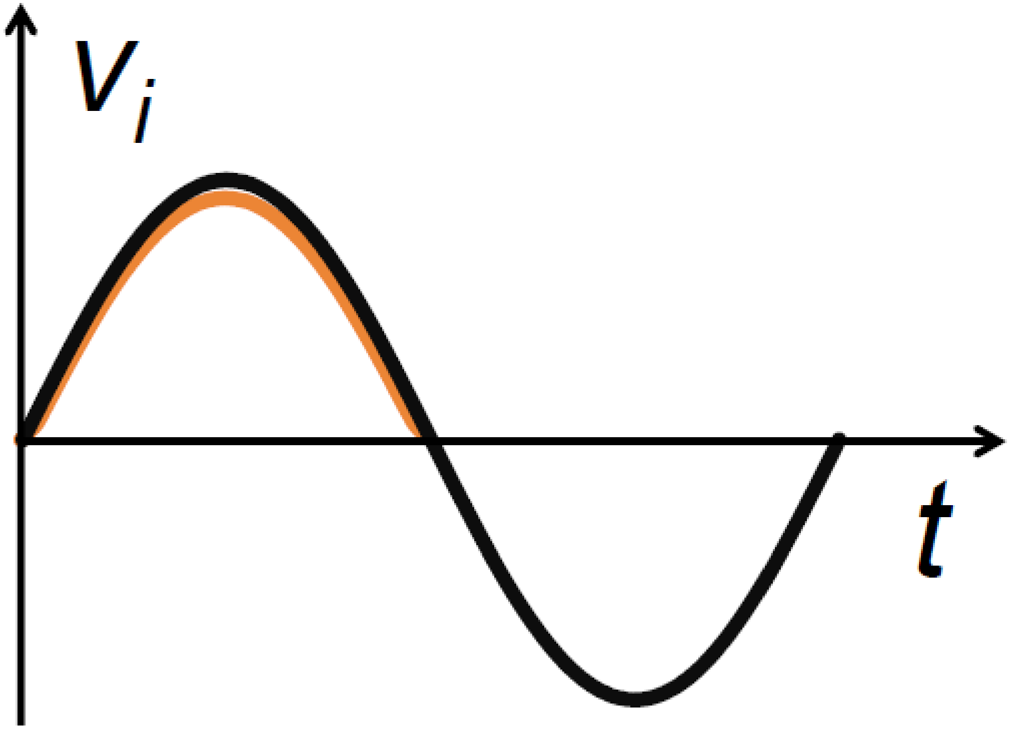
In the positive half cycle,

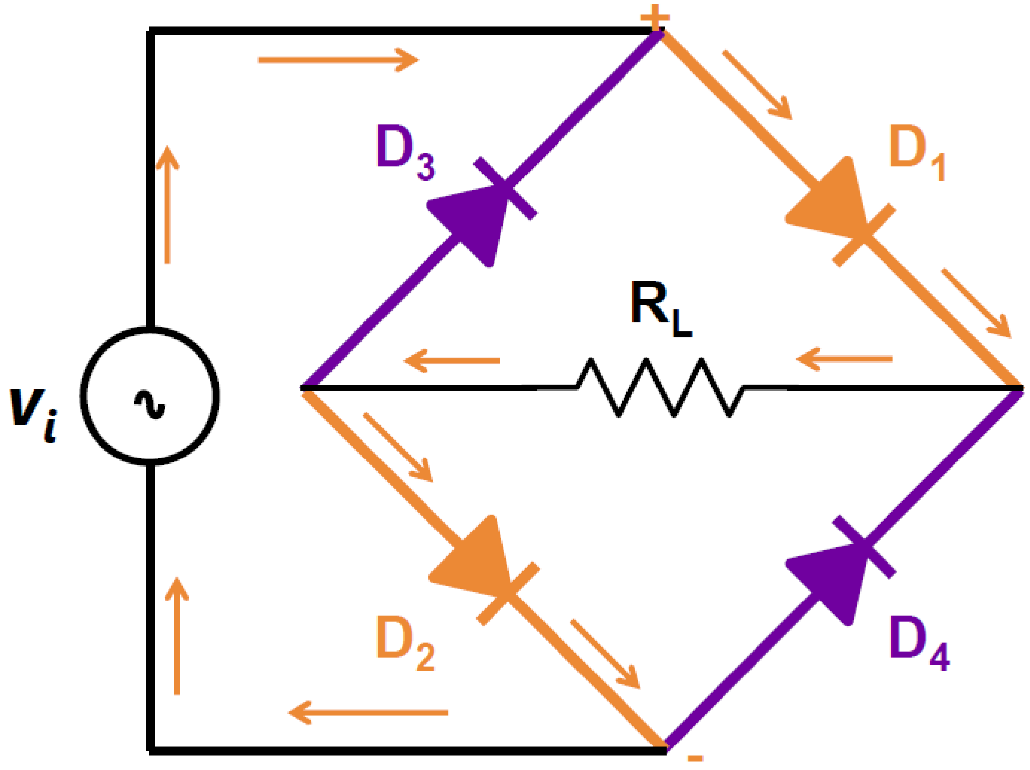
– Diodes D3 and D4 are cut-off

– Diodes D1 and D2 conduct

– Current passes through

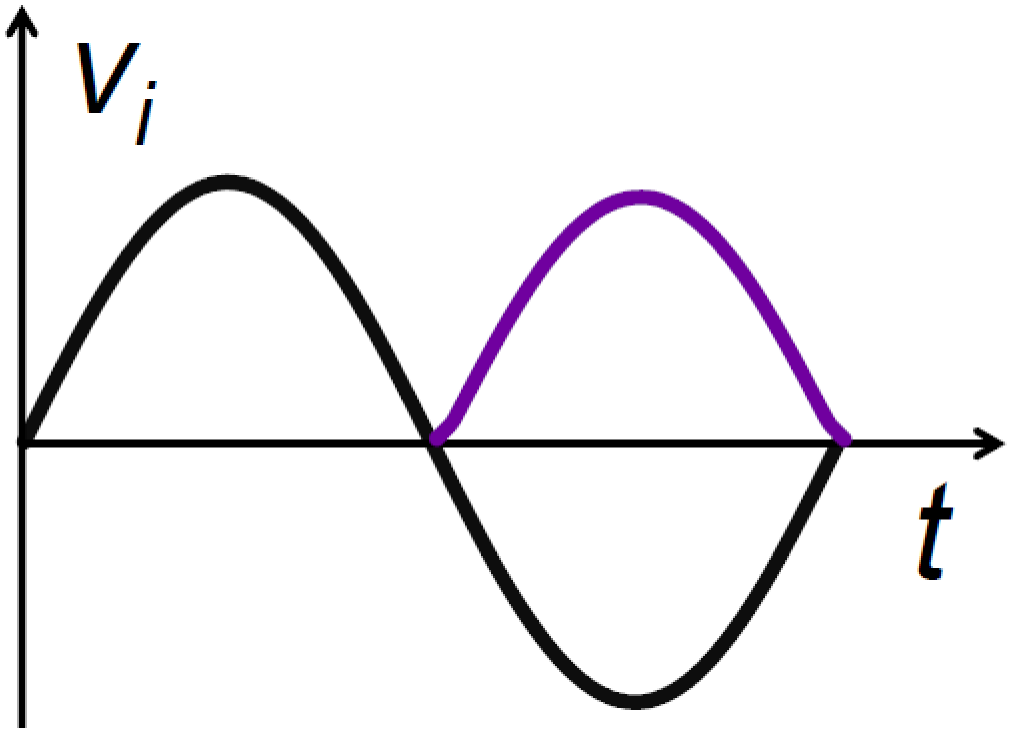
D_1-R_L-D_2

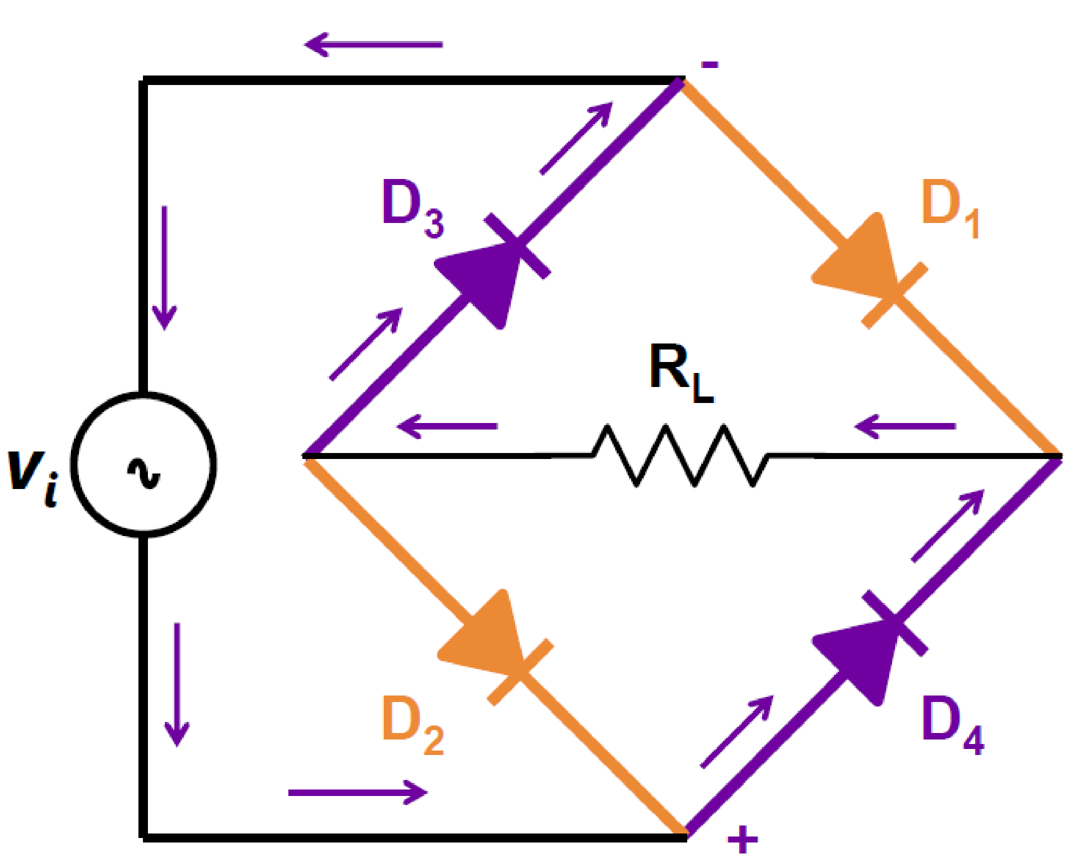




Full Wave Rectifier Circuits

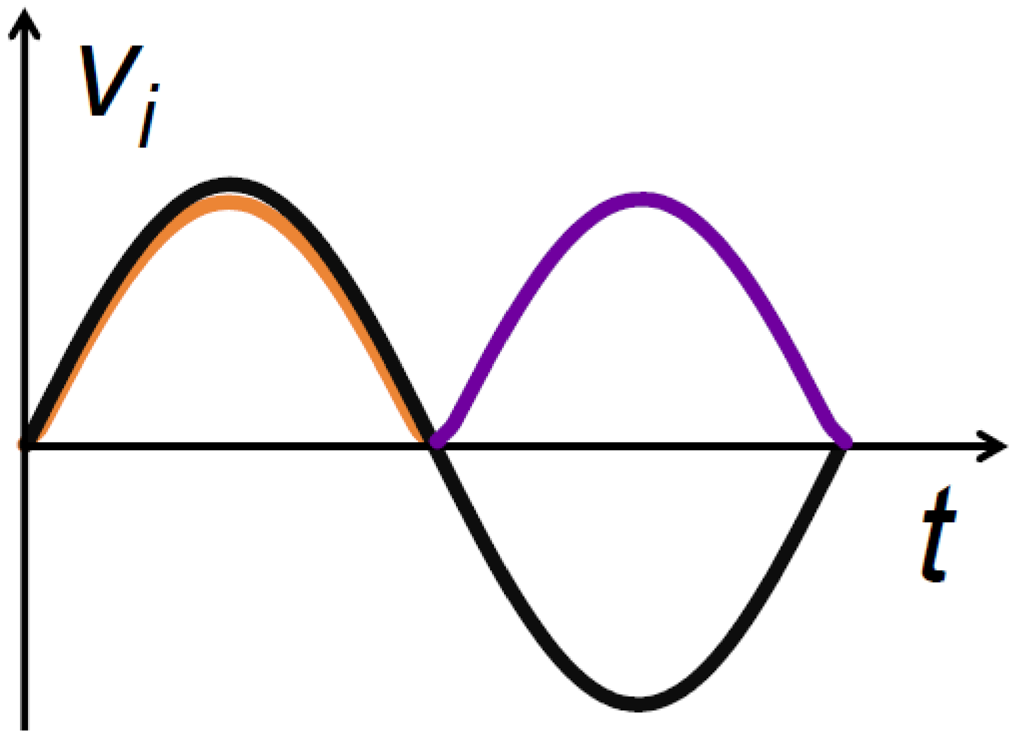
In the negative half cycle,
– Diodes D1 and D2 are cut-off
– Diodes D4 and D3 conduct
– Current passes through D4-R_L-D3

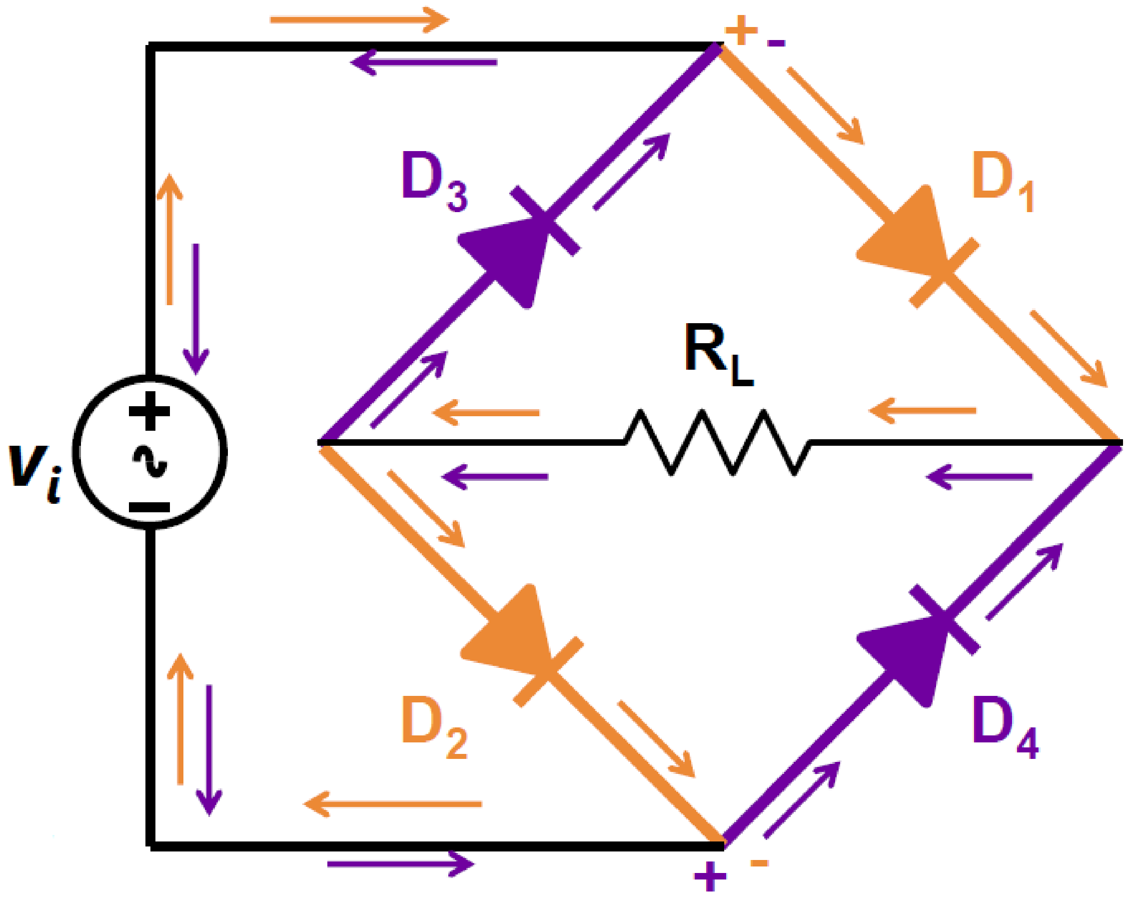




Full Wave Rectifier Circuits

In both the cycles





Full Wave Rectifier Circuits

- Consider a full wave circuit during the positive half cycle.
- Assume all the four diodes are identical
- Applying KVL,

$$v_i = 2v_D + v_0$$

Here, v_o is the output voltage across the load resistor R_L.

$$v_0 = i_D R_L$$

$$i_D = \frac{v_i - 2v_D}{R_L}$$