

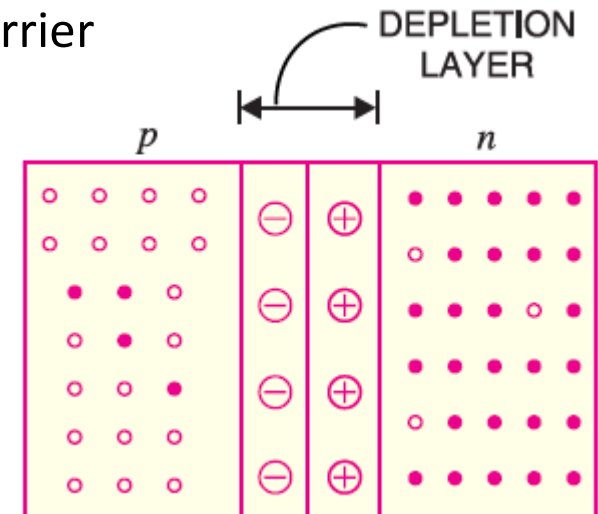
pn Junction Diode

- 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.

- 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 $N_D \text{ cm}^{-3}$
- p-region
 - Dopant atom: Trivalent
(Boron)
 - Doping concentration $N_A \text{ cm}^{-3}$

pn-junction: No electrical bias applied

- Diffusion effects – The holes and electrons move from area of high concentration to areas of low concentration.
- Holes and 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, $V_0 = 0.7 \text{ V}$; For germanium, $V_0 = 0.3 \text{ V}$



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

$$N_A \text{ cm}^{-3}$$

- Electrons are minority carriers

$$n_p = n_i^2 / N_A \text{ cm}^{-3}$$

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

On n-side

- Electrons are majority carriers

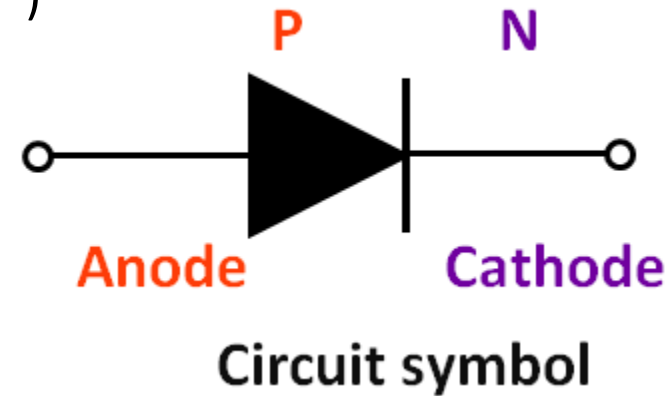
$$N_D \text{ cm}^{-3}$$

- Holes are minority carriers

$$p_n = n_i^2 / N_D \text{ cm}^{-3}$$

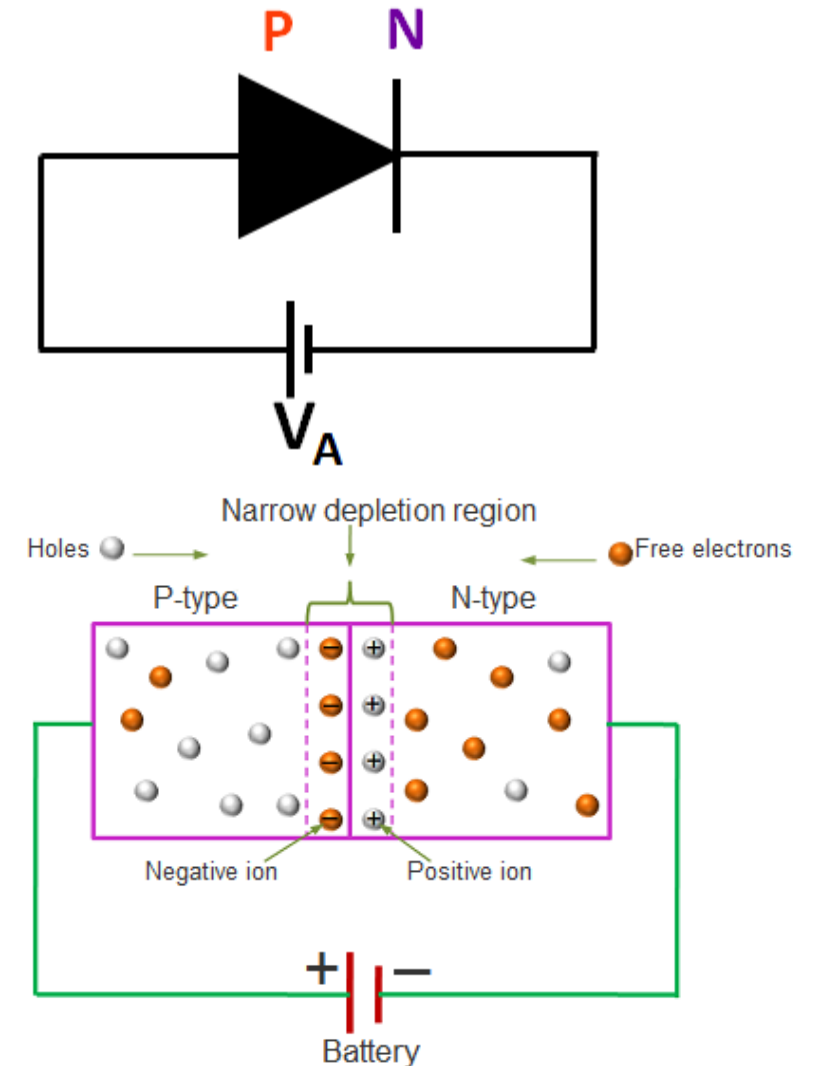
- Positively charged immobile dopant ions ($qN_D \text{ cm}^{-3}$)

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



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)



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

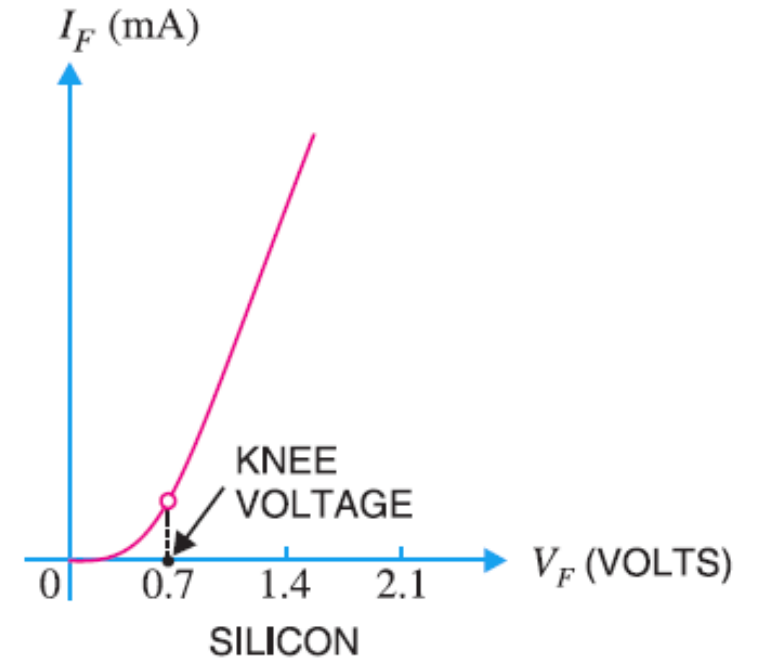
$$V_T = \frac{kT}{q}$$

k– Boltzmann's Constant

T– Absolute Temperature

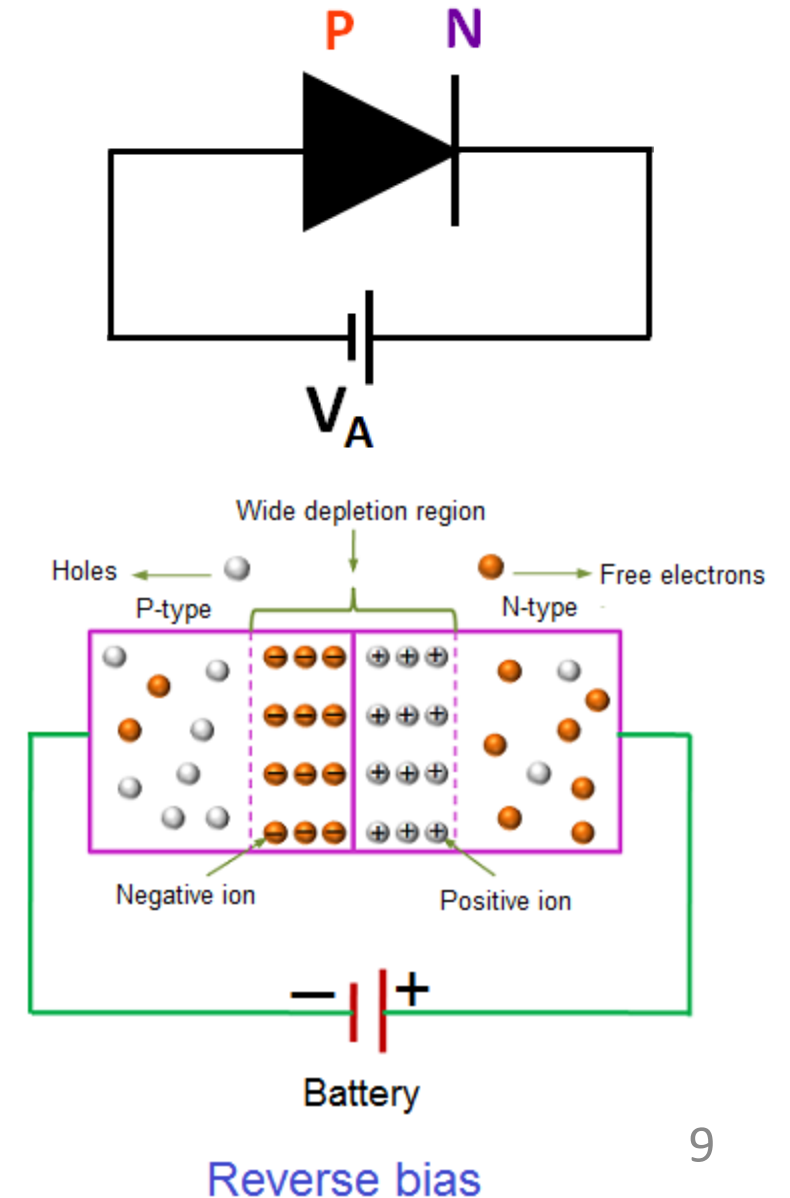
q– Electronic Charge

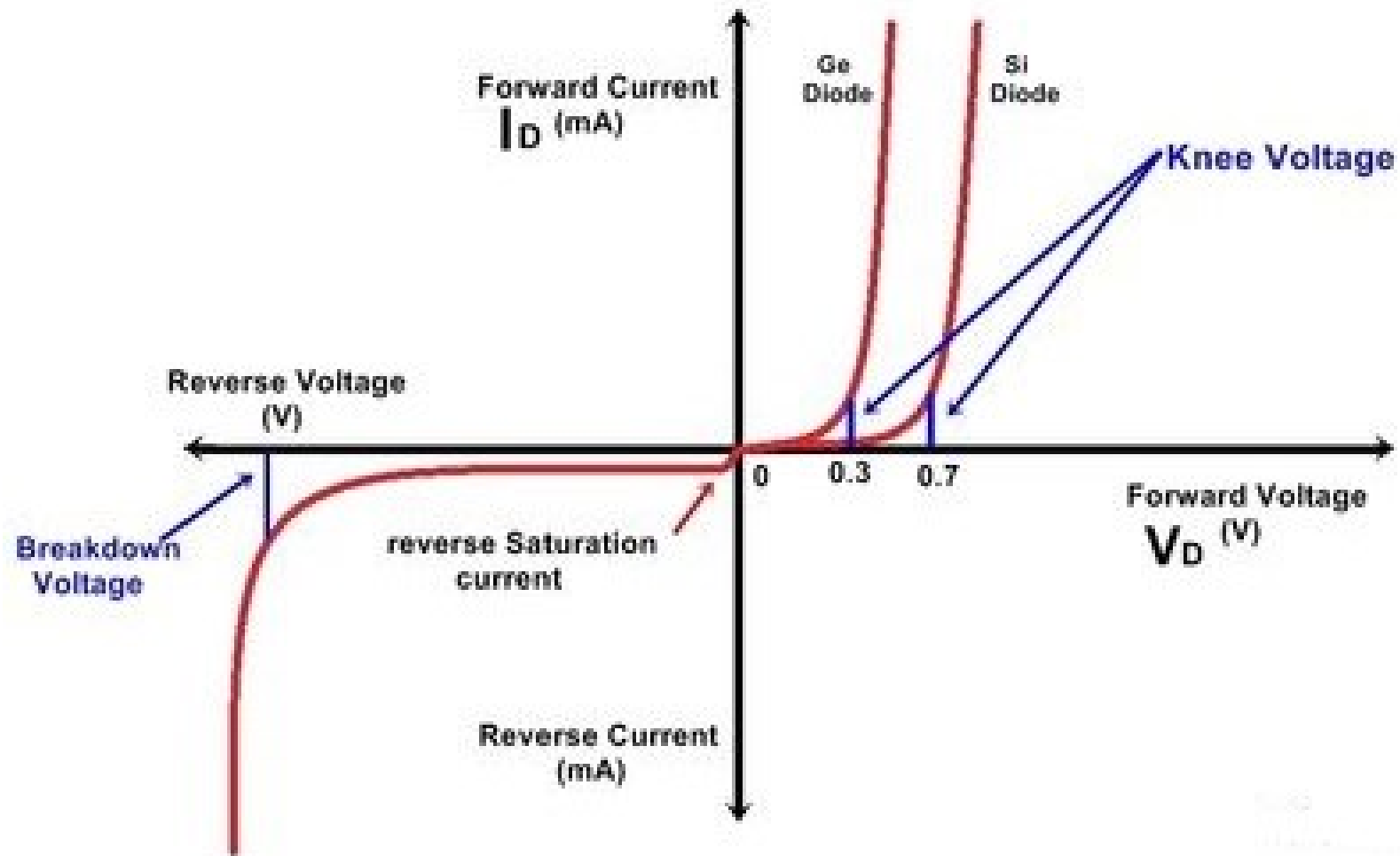
n – ideality factor, a number between 1 and 2



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 \rightarrow high electric field
- Depletion region eventually breaks down
- Reverse saturation current flows





P-N Junction Diode V-I Characteristics

- **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 Formulae

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

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

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

$$n = n_i e^{\frac{(E_F - E_i)}{kT}}$$

$$p = p_i e^{\frac{(E_i - E_F)}{kT}}$$

$$V_{bi} = \frac{kT}{q} \ln \left(\frac{N_A N_D}{n_i^2} \right) \quad \frac{kT}{q} = 26 \text{ mV}$$

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

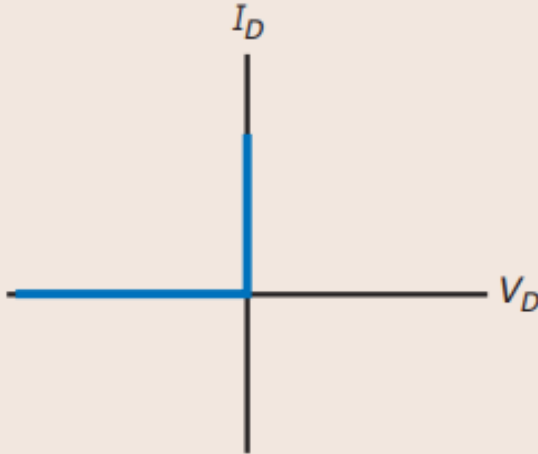
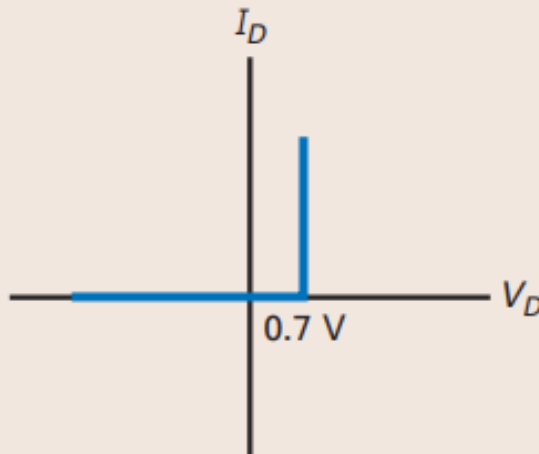
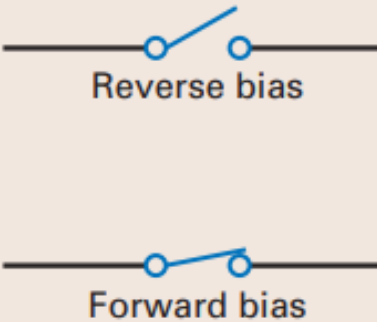
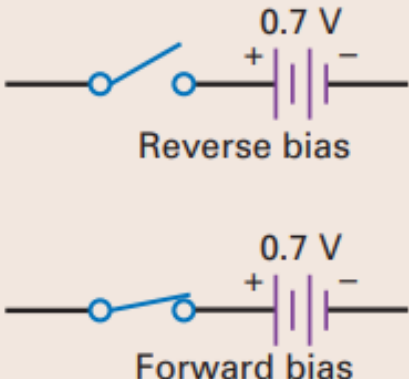
$$I_D \cong I_S \exp \left(\frac{V_D}{V_T} \right)$$

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

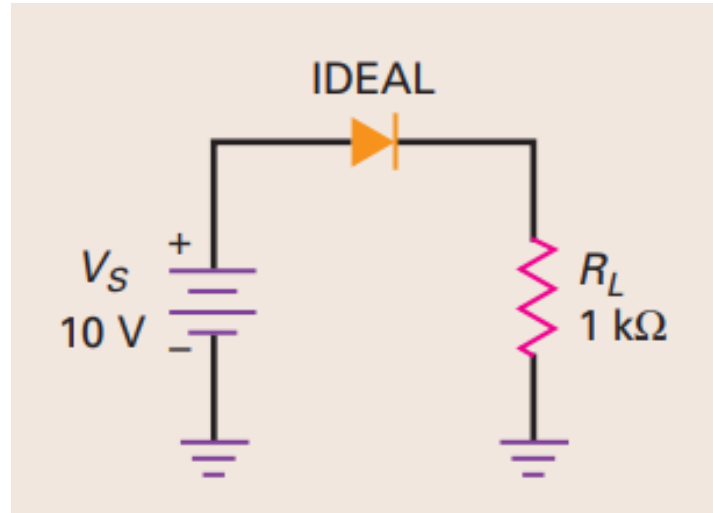
Diode Circuits

Ideal Diode

Practical Diode

	Ideal Diode	Practical Diode
Diode curve		
Equivalent circuit	 <p>Reverse bias</p> <p>Forward bias</p>	 <p>0.7 V</p> <p>Reverse bias</p> <p>0.7 V</p> <p>Forward bias</p>

Example : Use the ideal diode to calculate the load voltage and load current in given figure.



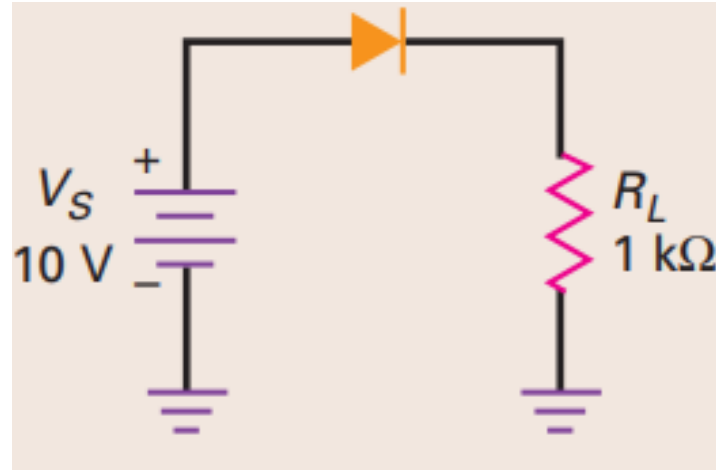
Since the diode is forward biased, it is equivalent to a closed switch. All of the source voltage appears across the load resistor:

$$V_L = 10 \text{ V}$$

With Ohm's law, the load current is:

$$I_L = \frac{10 \text{ V}}{1 \text{ k}\Omega} = 10 \text{ mA}$$

Example : Use the practical diode (Si) approximation to calculate the load voltage, load current, and diode power in given figure.



Since the diode is forward biased, it is equivalent to a battery of 0.7 V. The load voltage equals the source voltage minus the diode drop:

$$V_L = 10 \text{ V} - 0.7 \text{ V} = 9.3 \text{ V}$$

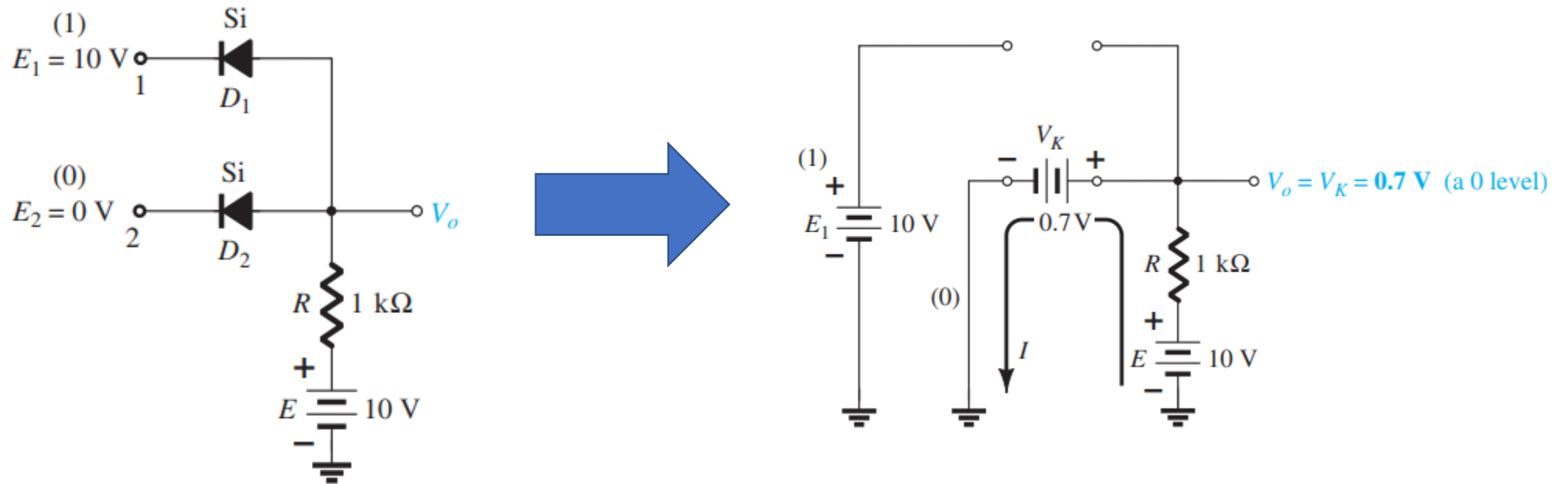
With Ohm's law, the load current is:

$$I_L = \frac{9.3 \text{ V}}{1 \text{ k}\Omega} = 9.3 \text{ mA}$$

The diode power is

$$P_D = (0.7 \text{ V})(9.3 \text{ mA}) = 6.51 \text{ mW}$$

Example : Find the current flowing through 1 k Ω resistance.

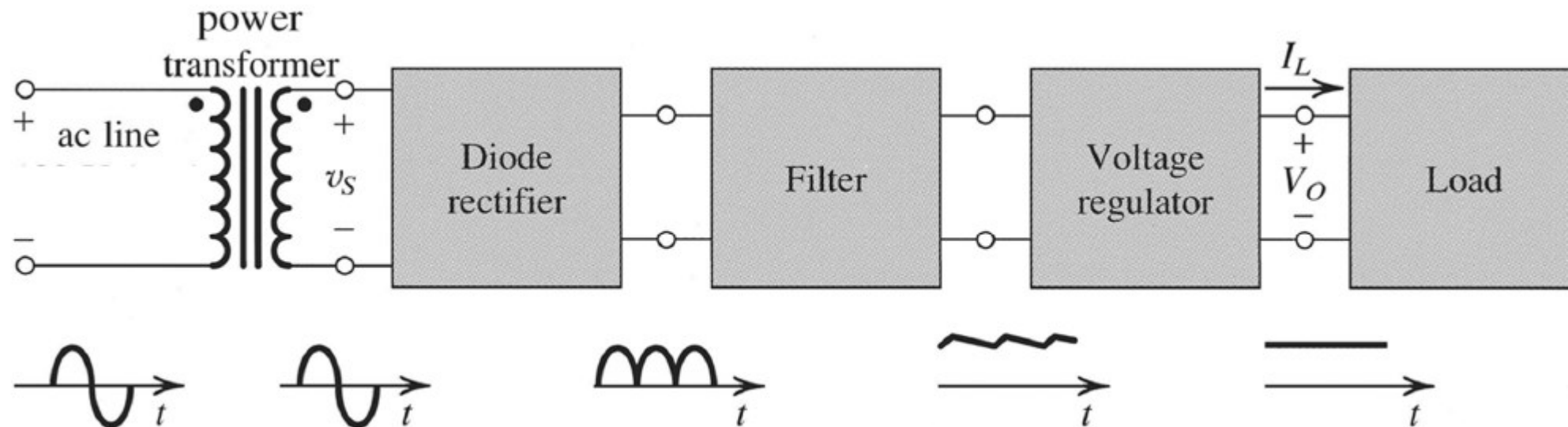


$$I = \frac{E - V_K}{R} = \frac{10\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega} = \mathbf{9.3\text{ mA}}$$

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),

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

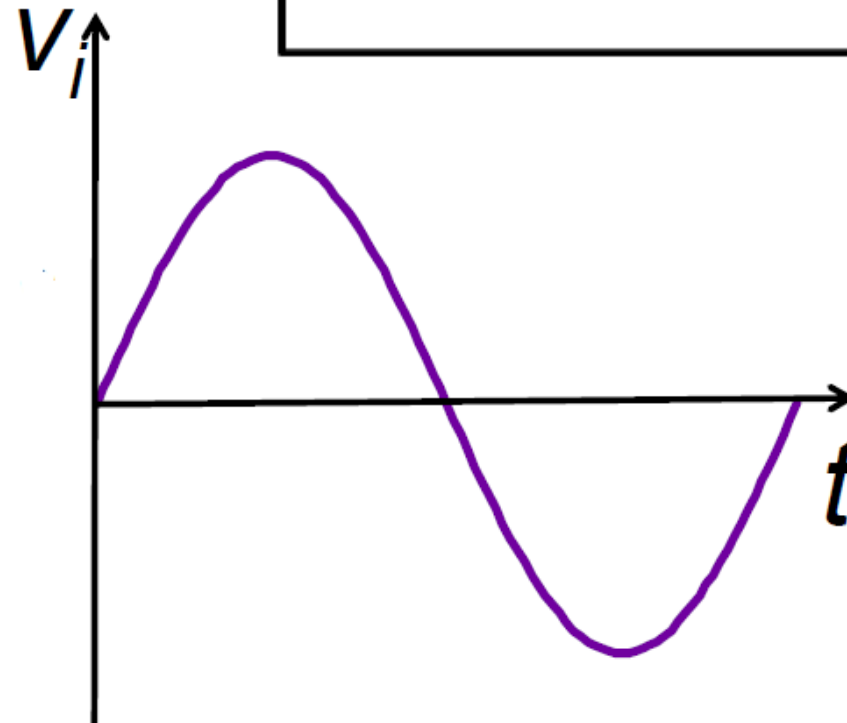
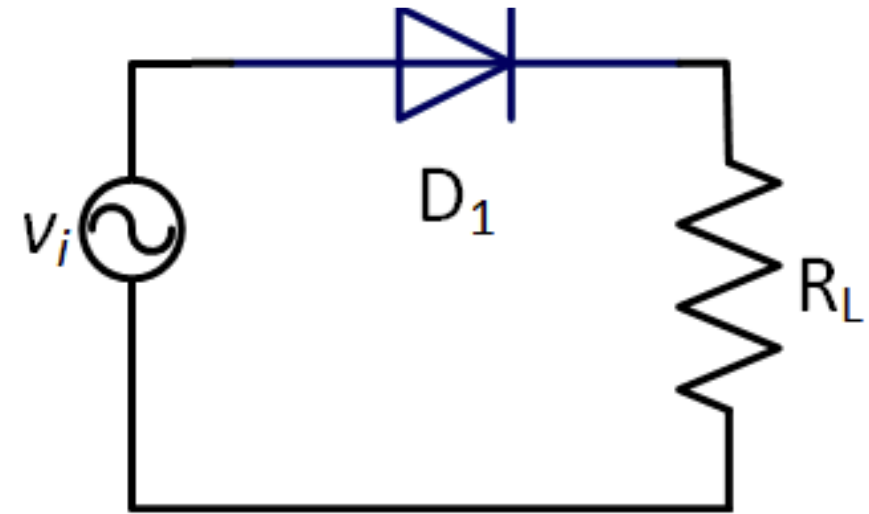
- Applying KVL,

$$v_i = V_D + v_o$$

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

$$v_o = i_D R_L$$

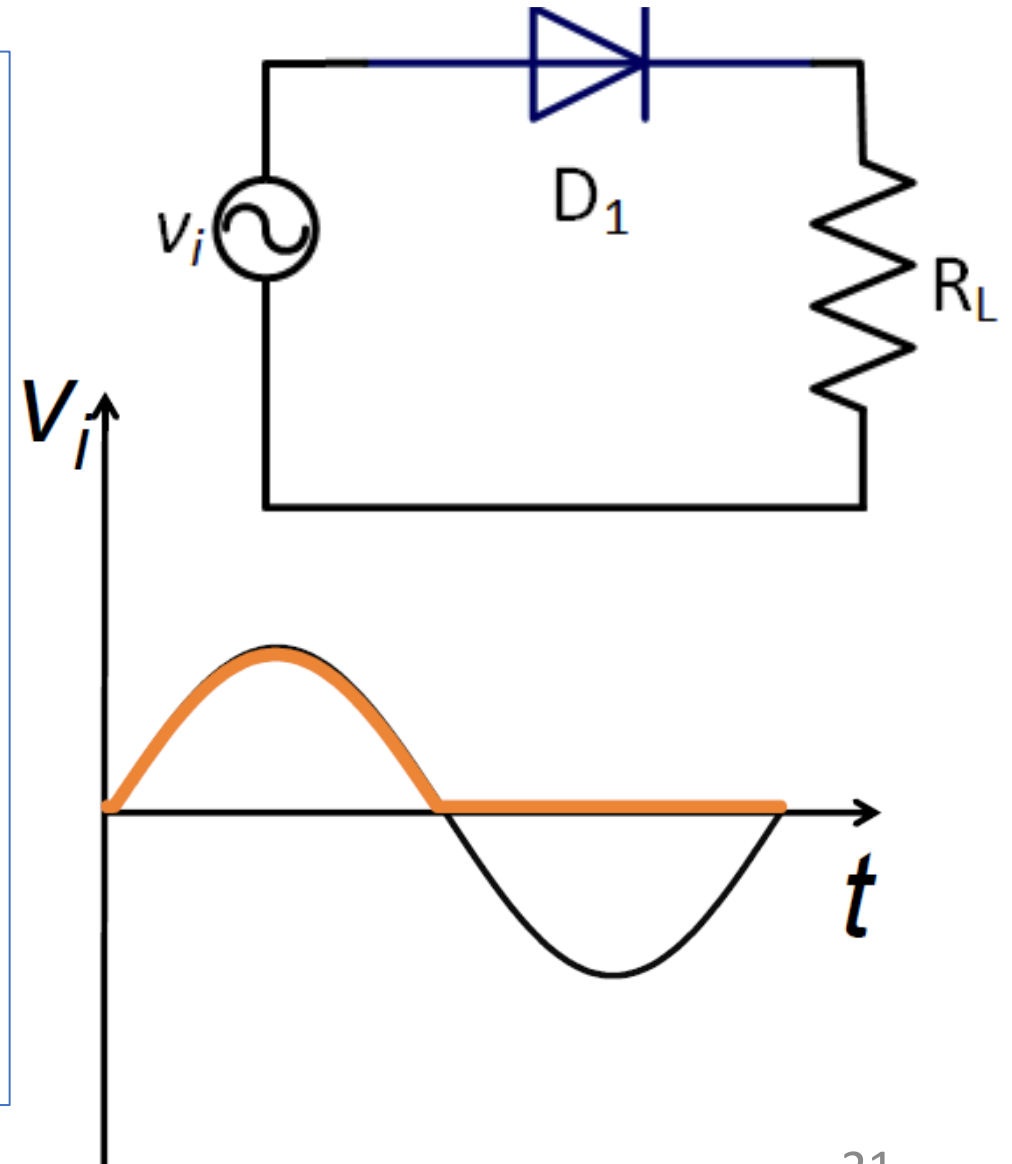
$$i_D = \frac{v_i - V_D}{R_L}$$



- 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**

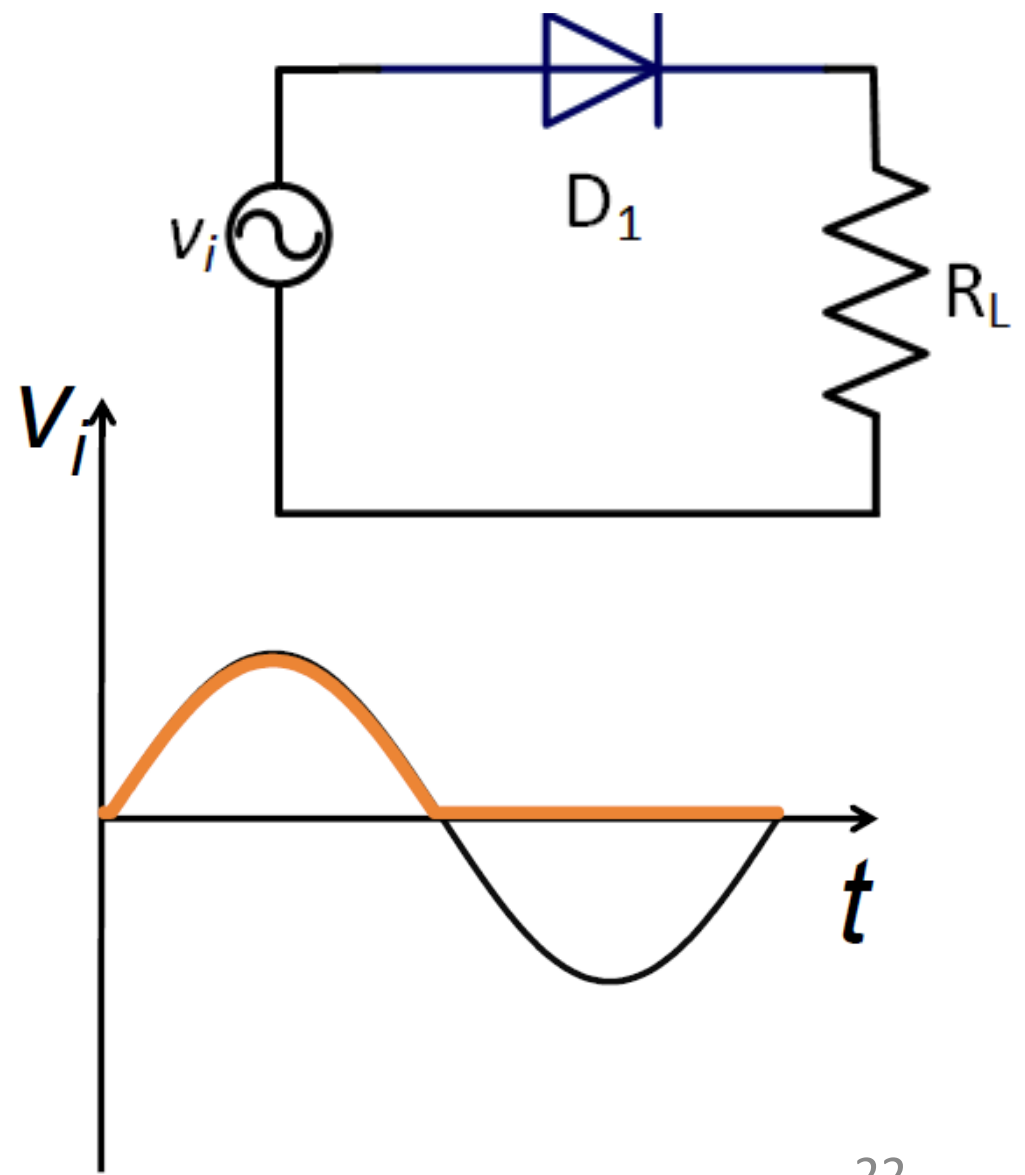
When $v_i > V_D$, the diode D_1 is on,

- 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 .**



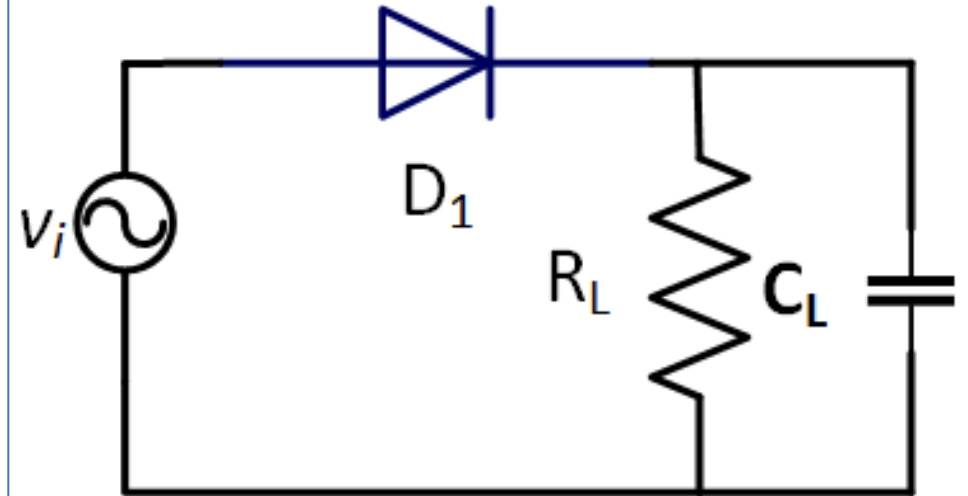
Half Wave Rectifier Circuits

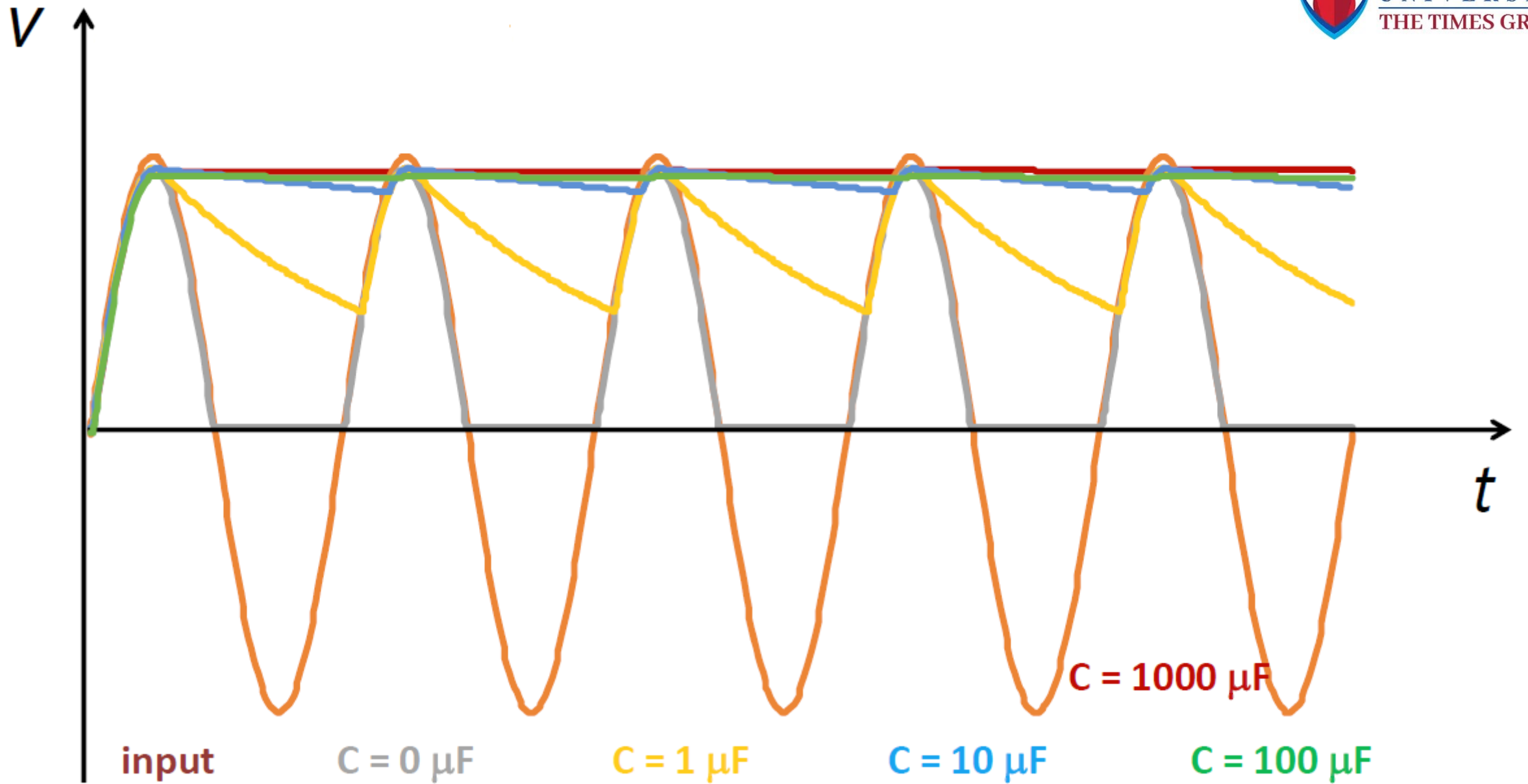
- In the negative half cycle,
 The diode D_1 is reverse biased
 - Diode is in cut-off mode
 - entire input voltage drops across the diode
 - current through the circuit $I_D = 0$
 - output voltage (v_o , voltage across R_L) is 0
 - no voltage across the load resistor



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

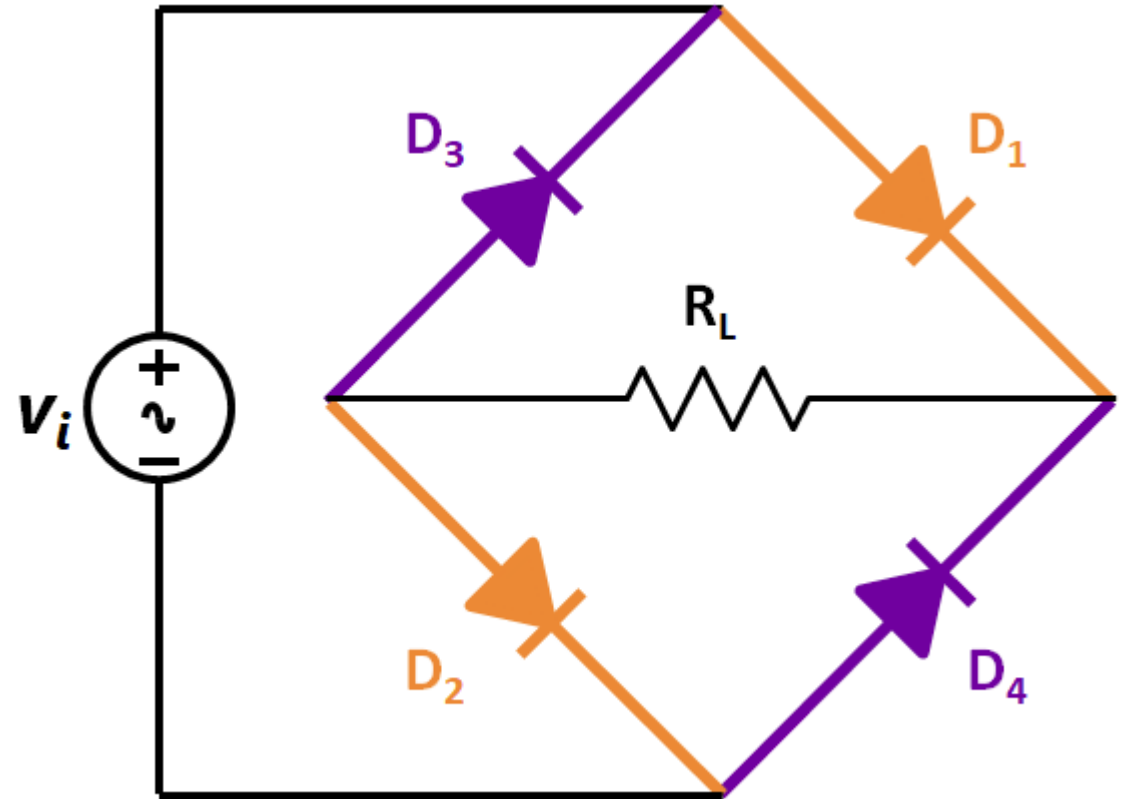




Full Wave Rectifier Circuits

- Full wave rectifier circuit is shown in figure
- The circuit contains four diodes (D_1 , D_2 , D_3 and D_4) and one load resistor (R_L) connected in series to an ac signal (v_i),

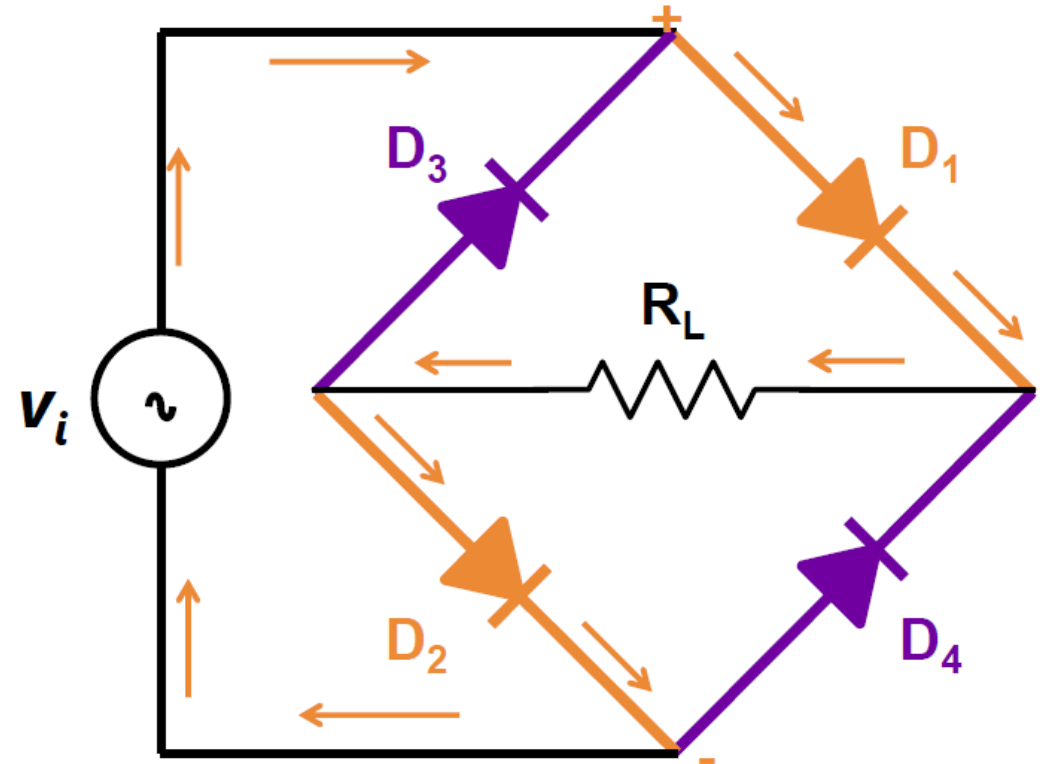
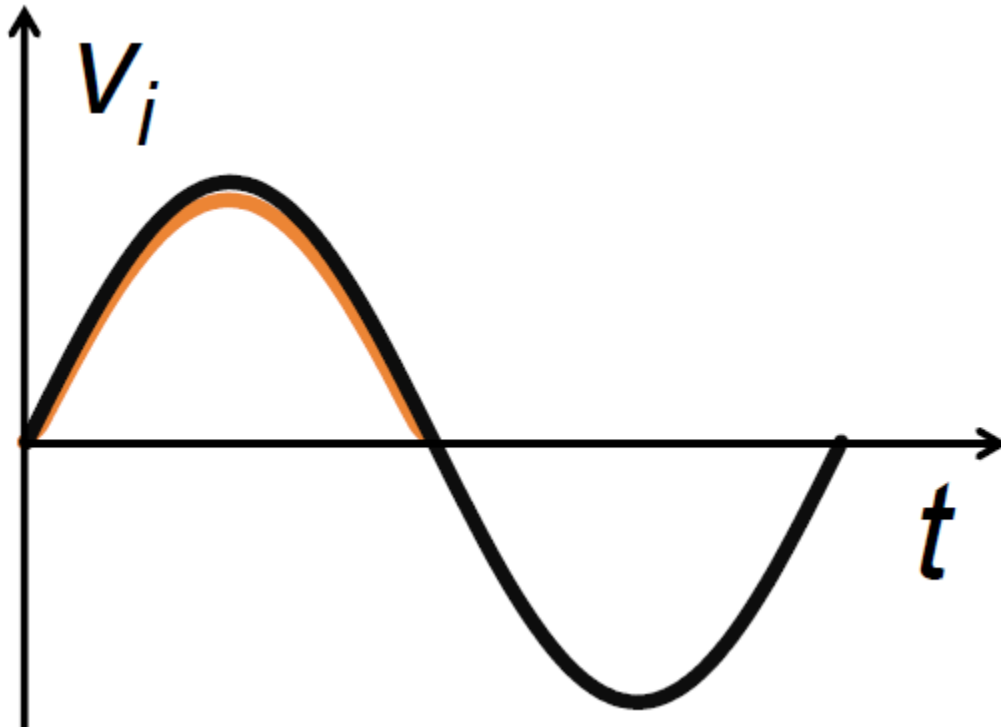
$$v_i = V_o \sin(\omega t)$$



Full Wave Rectifier Circuits

In the **positive half cycle**,

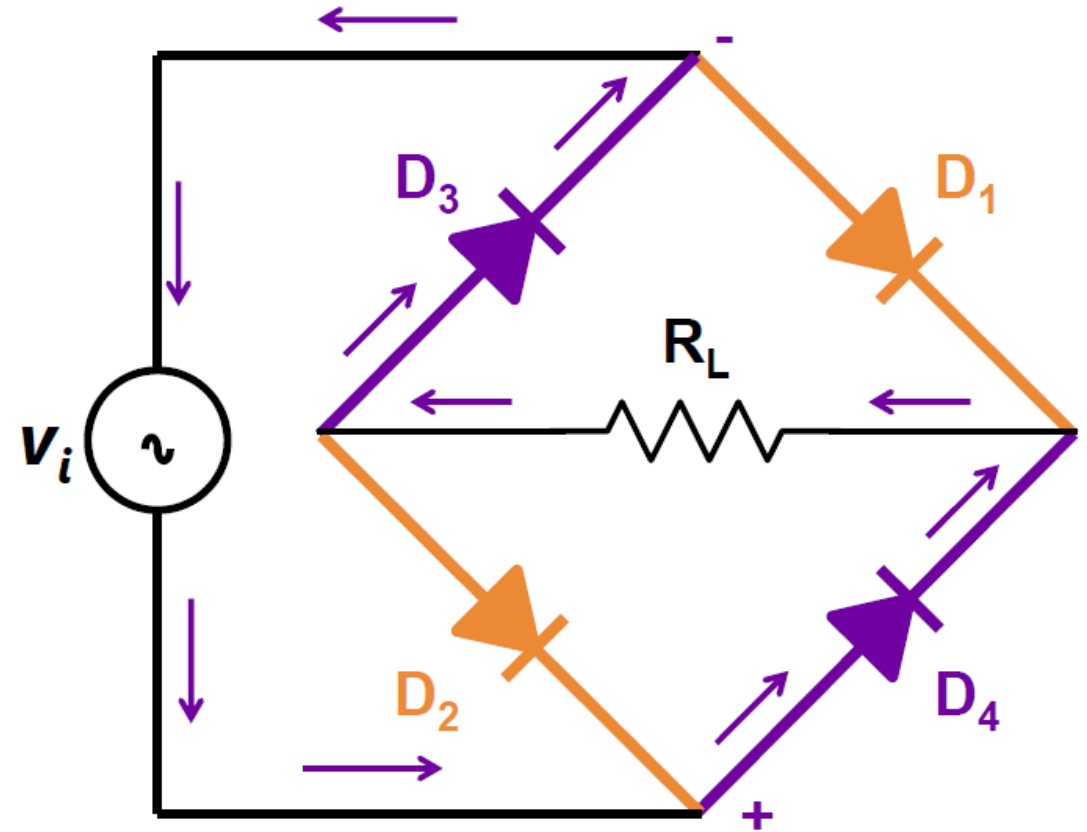
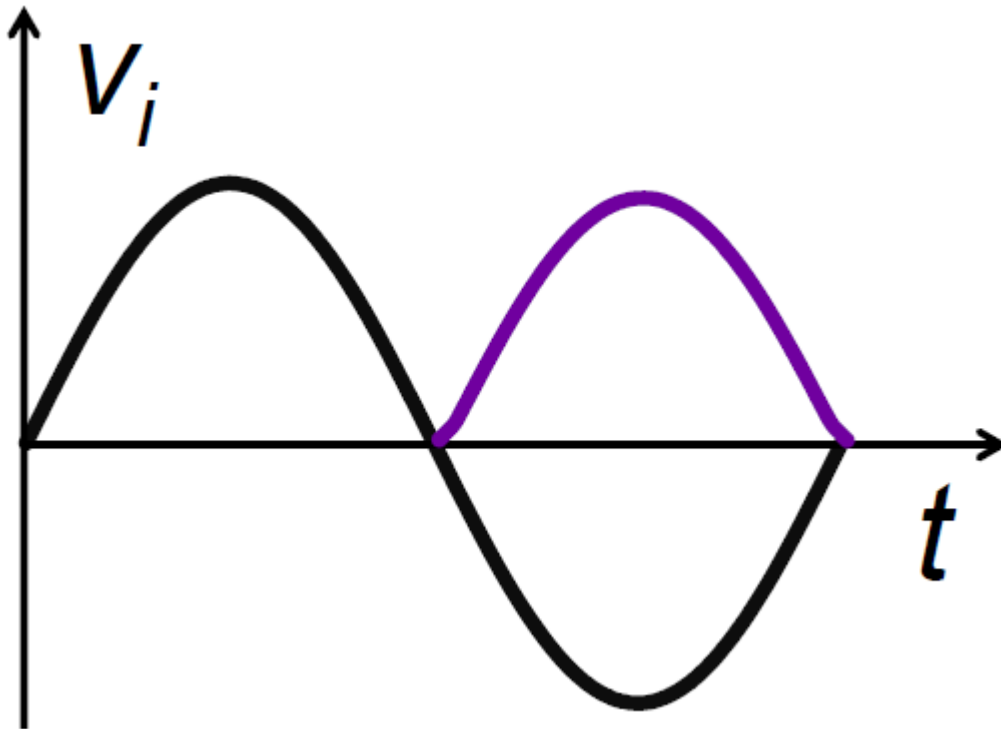
- Diodes D_3 and D_4 are **cut-off**
- Diodes D_1 and D_2 **conduct**
- Current passes through D_1 - R_L - D_2



Full Wave Rectifier Circuits

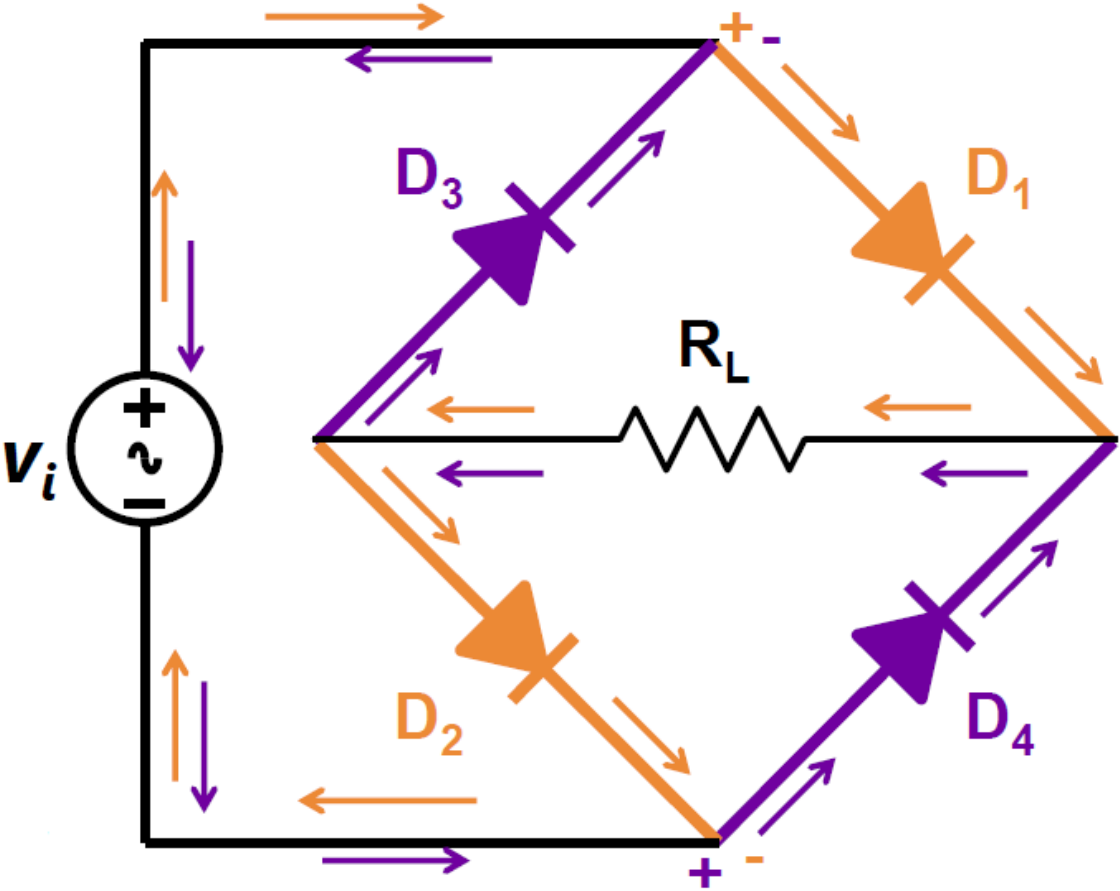
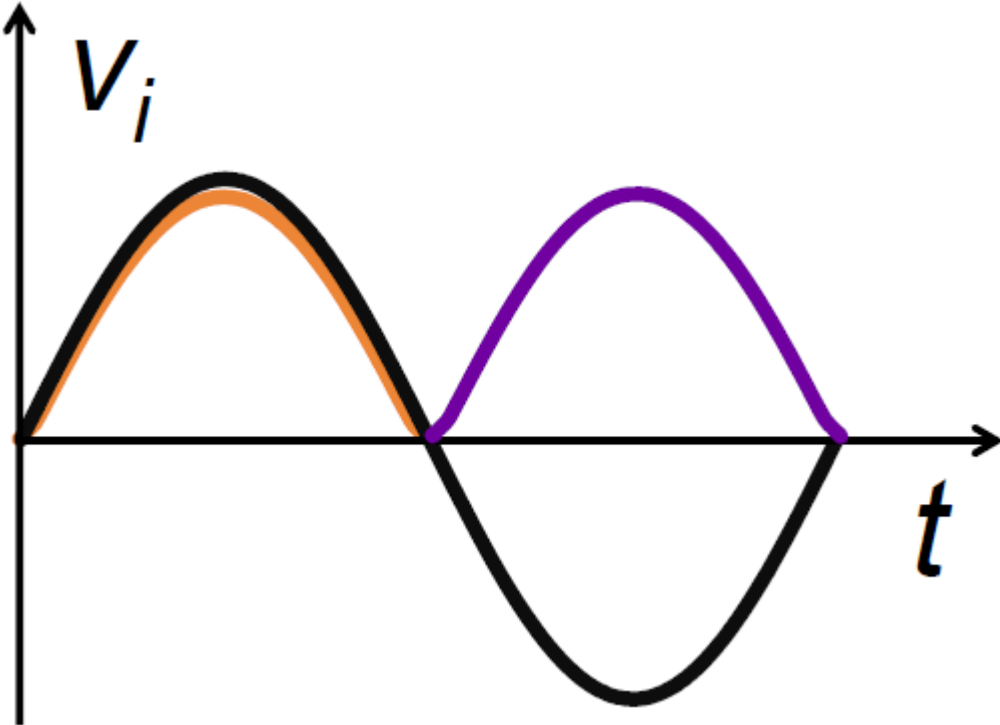
In the **negative half cycle**,

- Diodes D_1 and D_2 are **cut-off**
- Diodes D_4 and D_3 **conduct**
- Current passes through D_4 -
 R_L - D_3



Full Wave Rectifier Circuits

In both the cycles



Full Wave Rectifier Circuits

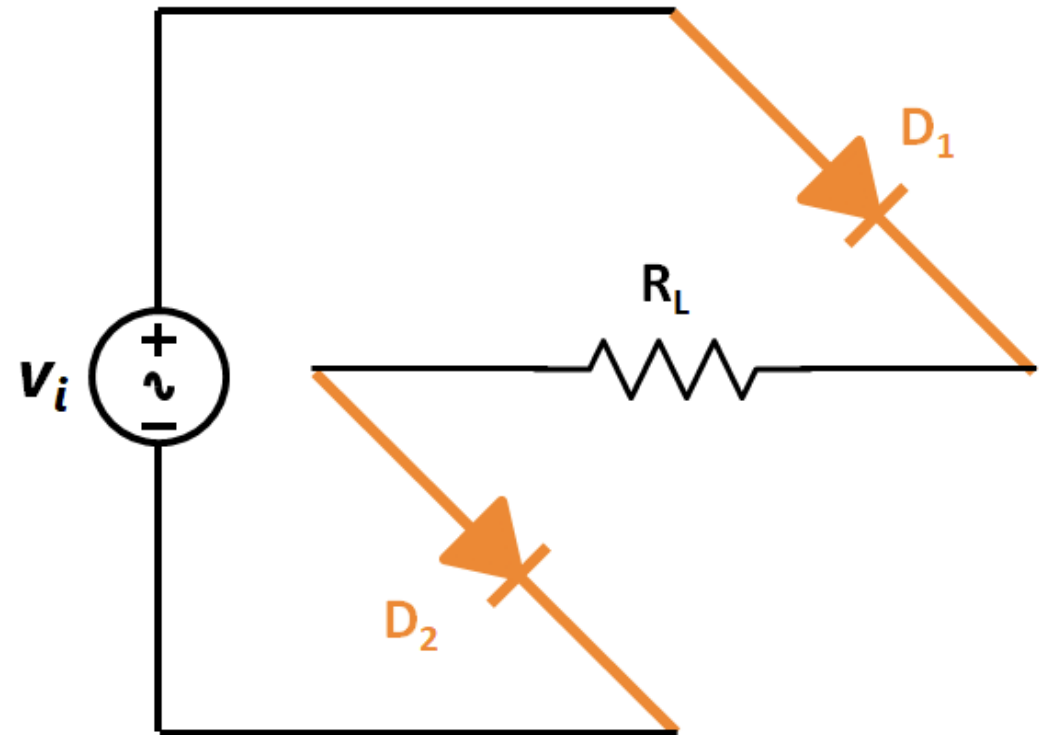
- Consider a full wave circuit during the positive half cycle.
- Assume all the four diodes are identical
- Applying KVL,

$$v_i = 2v_D + v_o$$

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

$$v_o = i_D R_L$$

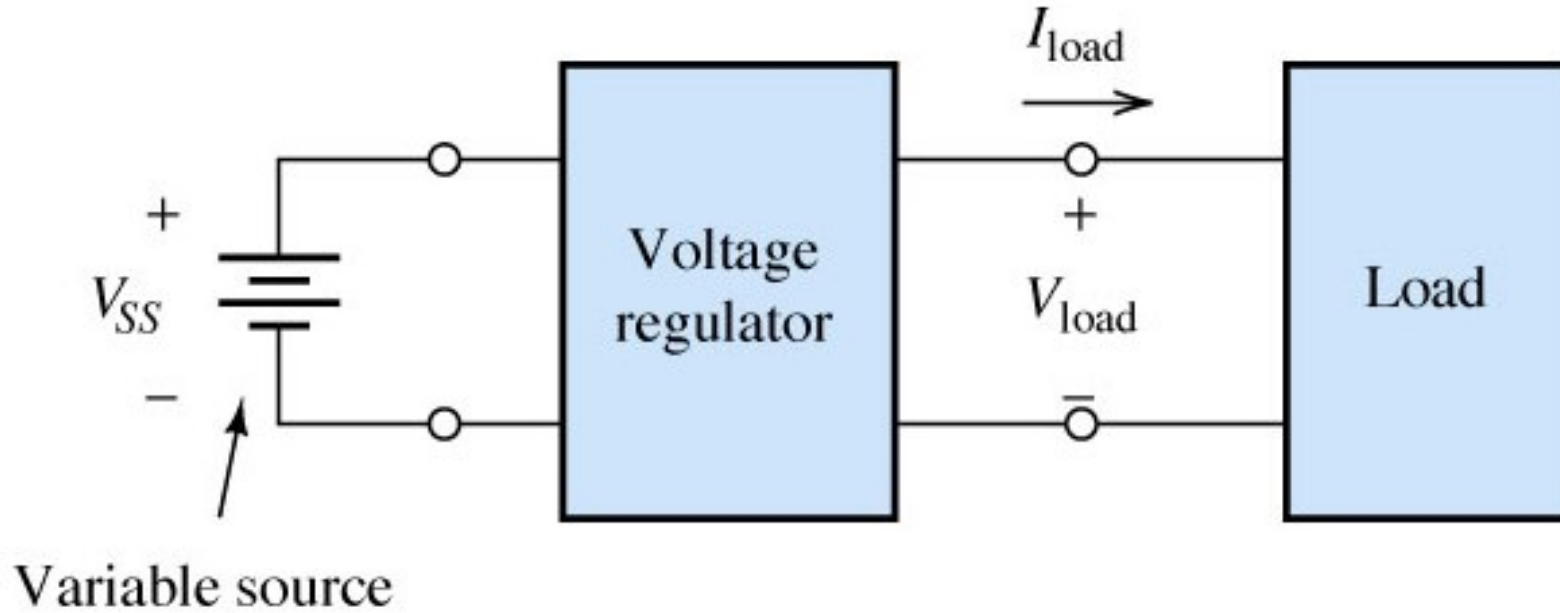
$$i_D = \frac{v_i - 2v_D}{R_L}$$



Voltage Regulator

Voltage Regulator

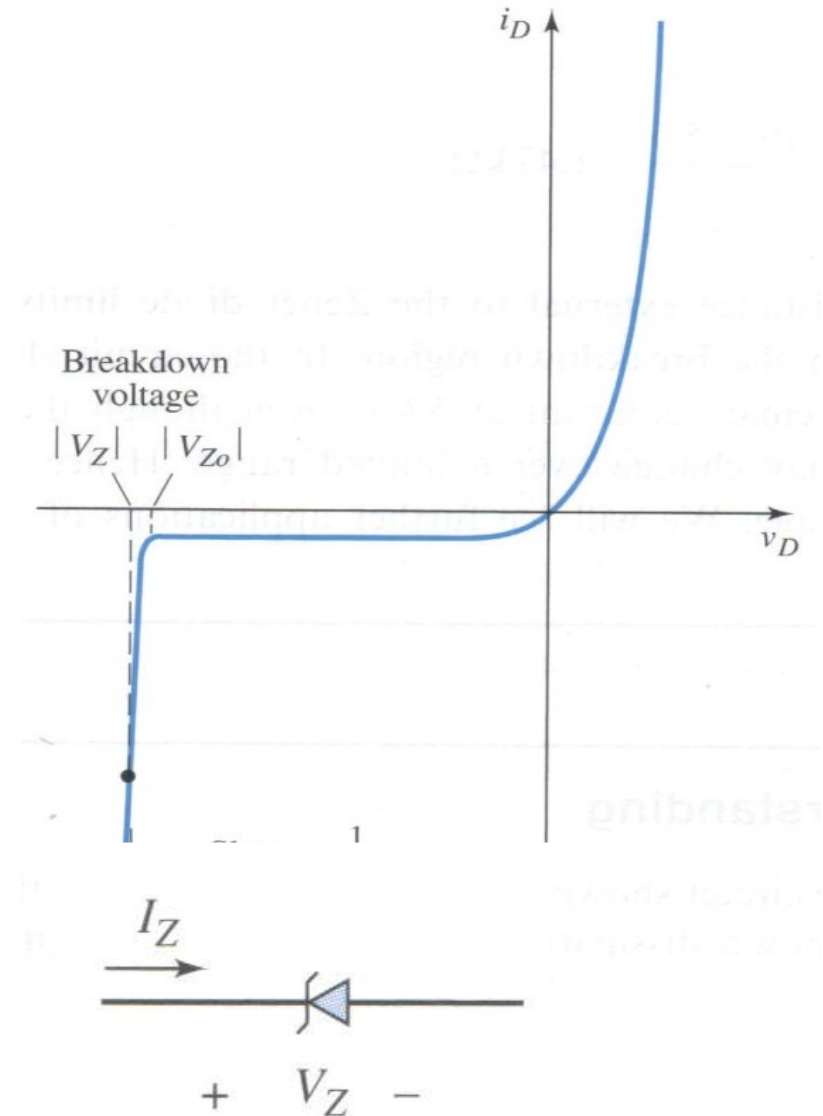
A voltage regulator supplies constant voltage to a load.



- A diode with a sharp breakdown voltage can be used as a constant voltage reference in a circuit.
- The applied reverse biased voltage cannot increase without limit since at some point breakdown occurs causing current to increase rapidly.
- The voltage at that point is known as the breakdown voltage, V_Z
- Diodes are fabricated with a specifically design breakdown voltage and are designed to operate in the breakdown region are called **Zener diodes**.

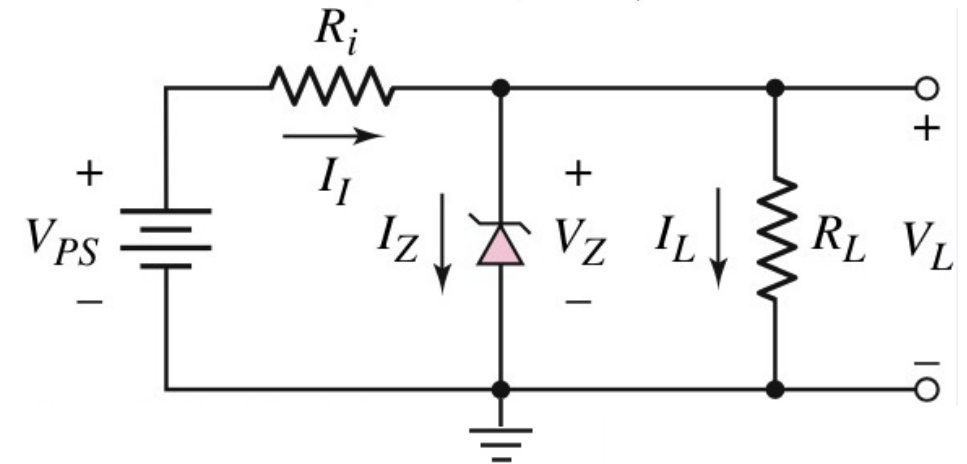
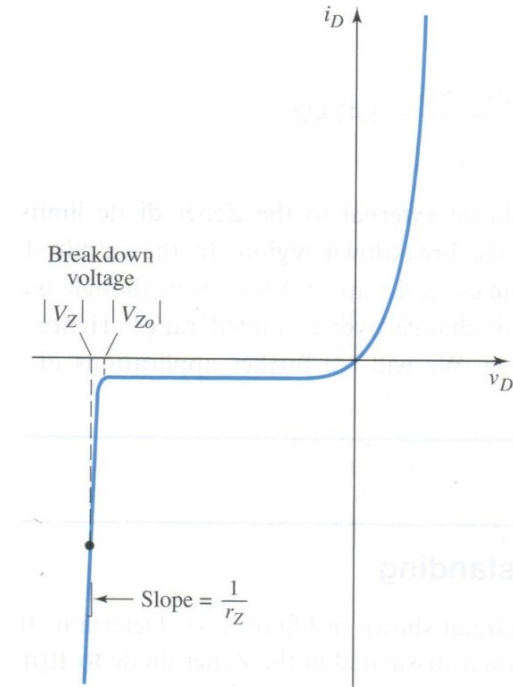
NOTE: A Zener diode when forward biased, it acts like a normal PN junction diode.

A Zener diode when reverse-biased, it acts at the breakdown region

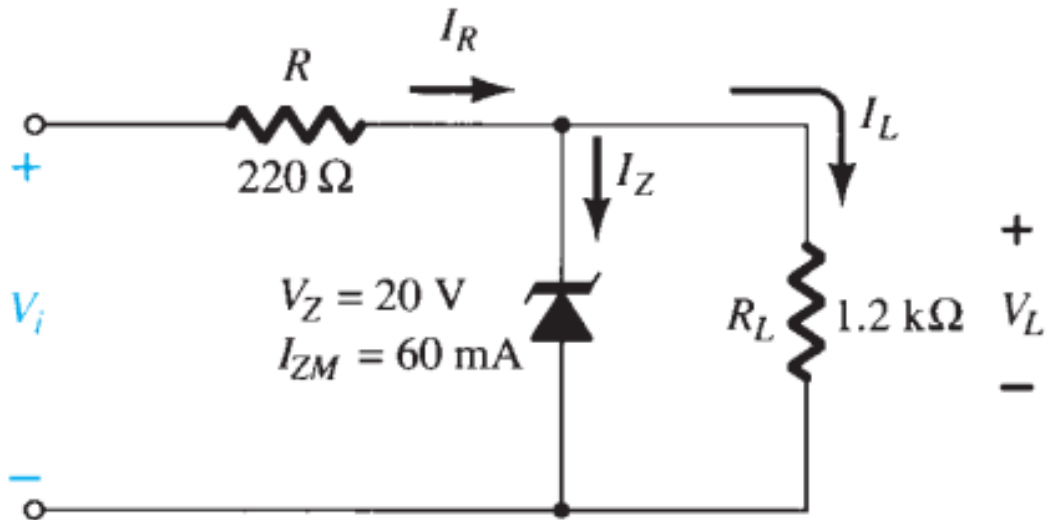


Zener Diode as Voltage Regulator

- The breakdown voltage of a Zener diode is nearly constant over a wide range of reverse-bias currents.
- This makes the Zener diode useful in a voltage regulator, or a constant-voltage reference circuit.
- The Zener diode holds the voltage constant regardless of the current
- The load resistor sees a constant voltage regardless of the current
- The remainder of V_{PS} drops across R_i



Example : Determine the range of values of V_i that will maintain the Zener diode given in below figure to the “on” state



$$V_{i_{\min}} = \frac{(R_L + R)V_Z}{R_L} = \frac{(1200 \Omega + 220 \Omega)(20 \text{ V})}{1200 \Omega} = \mathbf{23.67 \text{ V}}$$

$$I_L = \frac{V_L}{R_L} = \frac{V_Z}{R_L} = \frac{20 \text{ V}}{1.2 \text{ k}\Omega} = 16.67 \text{ mA}$$

$$I_{R_{\max}} = I_{ZM} + I_L = 60 \text{ mA} + 16.67 \text{ mA} = 76.67 \text{ mA}$$

$$\begin{aligned}
 V_{i_{\max}} &= I_{R_{\max}} R + V_Z \\
 &= (76.67 \text{ mA})(0.22 \text{ k}\Omega) + 20 \text{ V} \\
 &= 16.87 \text{ V} + 20 \text{ V} \\
 &= \mathbf{36.87 \text{ V}}
 \end{aligned}$$