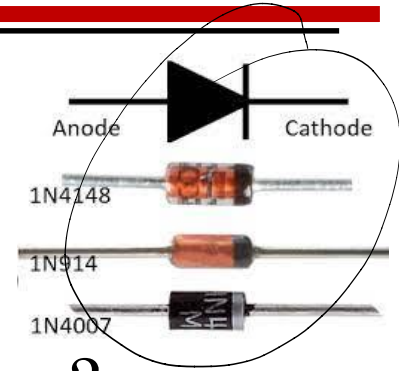


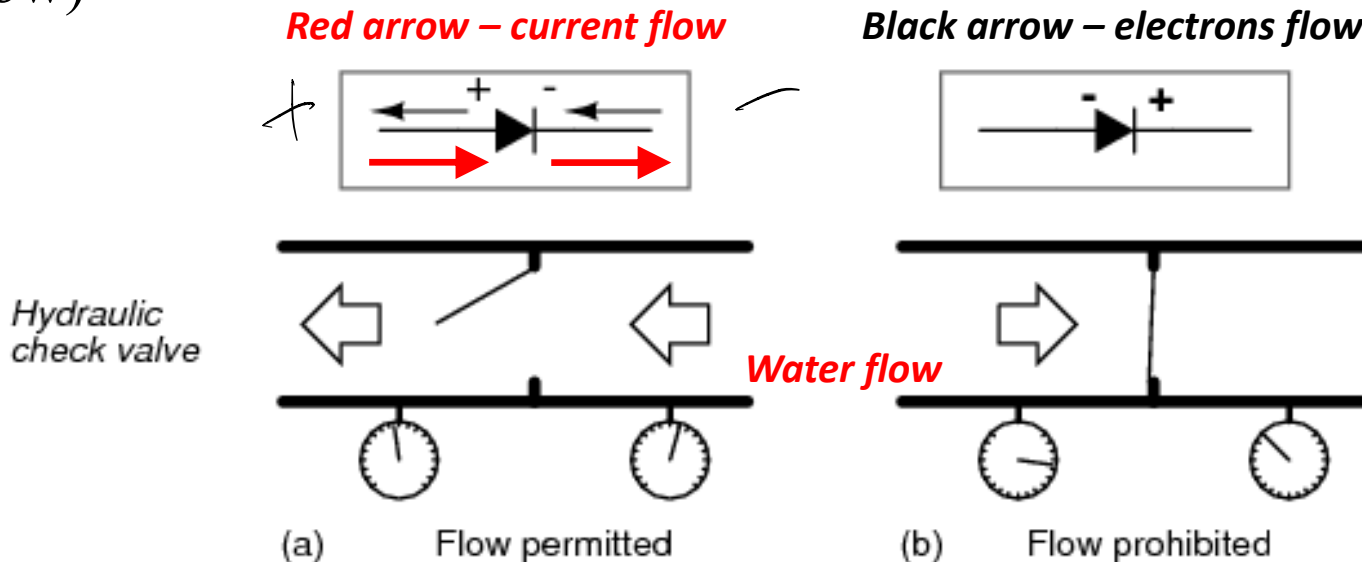
Diode Circuits

- 1) What is the property of a diode?
- 2) How is it being made?
- 3) How does a Diode work?
- 4) What electrical (V-I) characteristic do it have?
- 5) How to calculate a diode voltage and its current in an electrical circuit?
- 6) How to model a diode characteristic under large a signal operation?
- 7) What are its applications?
- 8) Zener diode – a special type of diode



What is the properties of a diode?

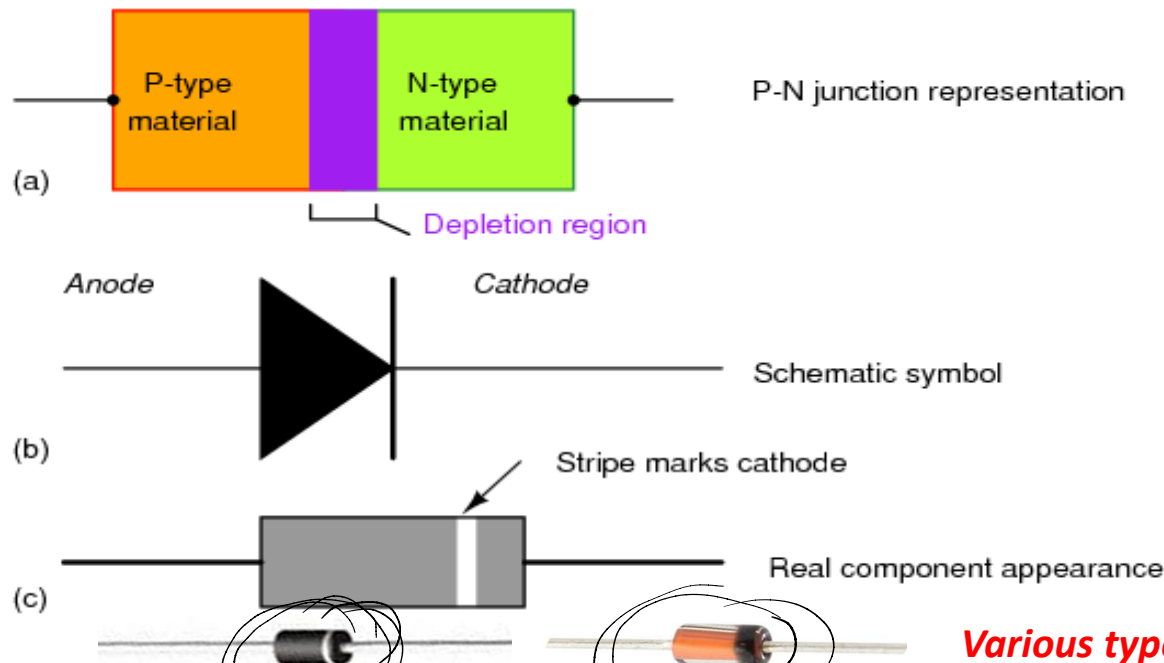
- It is a component that restricts the direction of movement of charge carriers.
- It allows an electric current to flow in one direction but not the other way round.
- Current flow (**red arrow**) is opposite to electrons flow (black arrow)



<http://electric-circuit.blogspot.com/2008/08/diodes-and-rectifiers.html>

How is it being made?

- It is made of joining P-type semiconductor materials and N-type semiconductor materials.
- The terminal at the P-type material is called the anode. In contrast, the terminal at the N-type material is called the cathode.



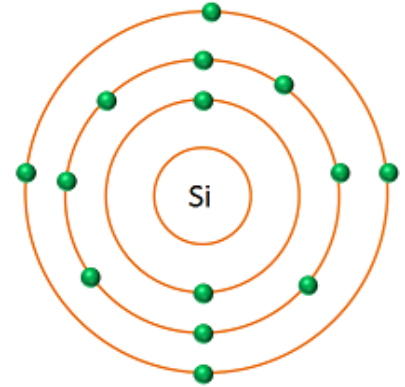
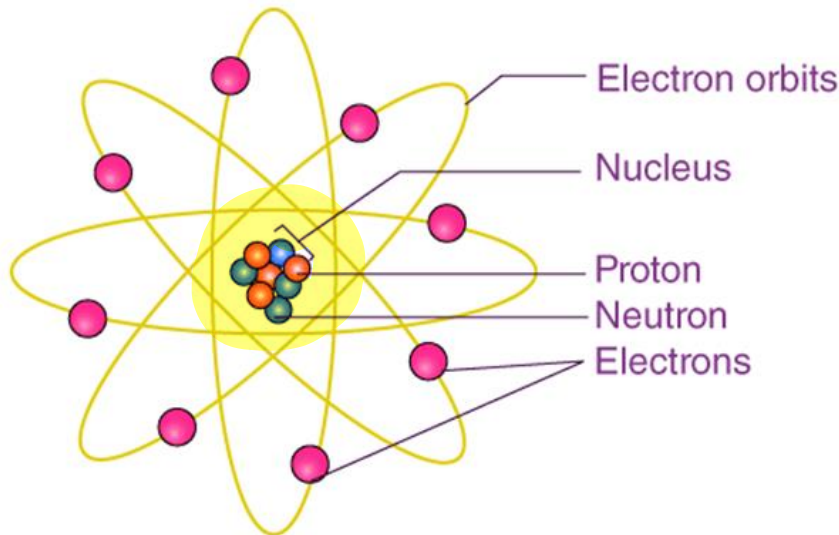
Various types of diode

<http://electric-circuit.blogspot.com/2008/08/diodes-and-rectifiers.html>

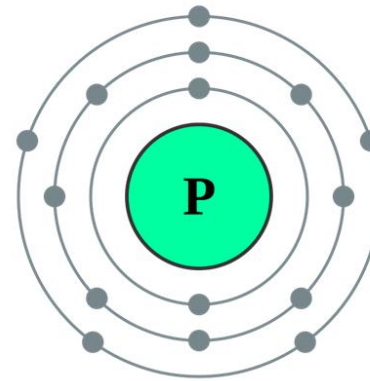
What is Semiconductor material?
What do p-type and n-type mean?

The basic structure of matters

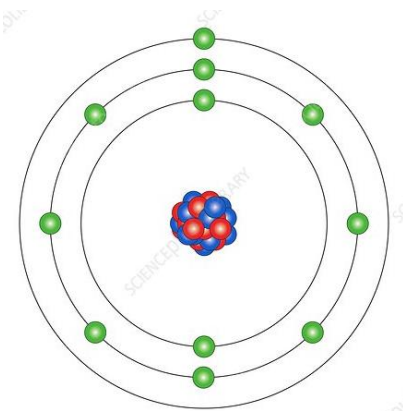
- All matter is made of atoms
- Different atoms have a different number of electrons, protons and neutron.
- Different materials having different electrical conductivities depends on the number of outer electrons and how its bonds with other atoms



Silicon



Phosphorus



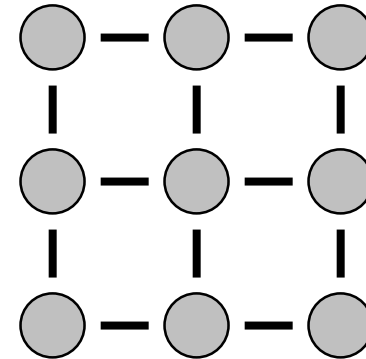
Sodium

Electrical Materials

Insulators

Electrons are bound to the nucleus and are therefore not free to move

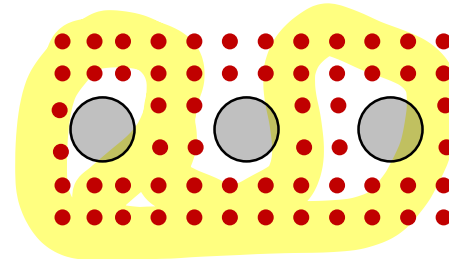
With no free electrons, conduction cannot occur



Conductors

Sea of free electrons not bound to the atoms

Ample availability of free electrons allows for electrical conduction



Semiconductors

Electrons are bound to the nucleus but vacancies are created due to thermal excitation

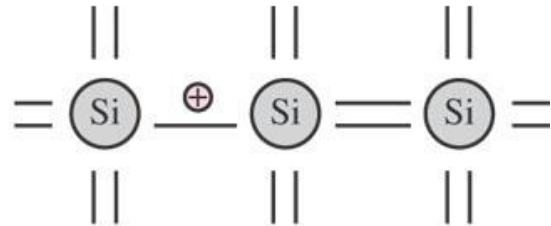
Electrical conduction occurs through positive (called holes) and negative (electrons) charge carriers

Electrons: mobile negative charge carriers

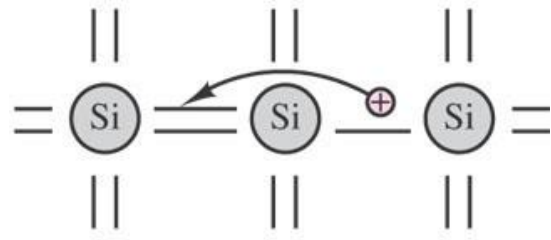
Holes: mobile positive charge carriers

Intrinsic semiconductors and conduction

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.



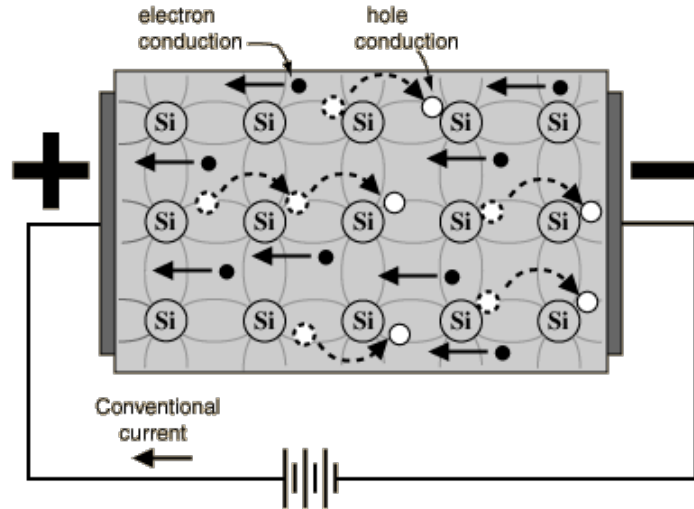
⊕ = Hole Electron jumps to fill hole



The net effect is a hole moving to the right

A vacancy (or hole) is created whenever a free electron leaves the structure.

This “hole” can move around the lattice if other electrons replace the free electron.



Each Si atom has 4 valence electrons and contributes 1 electron per bond
Each bond is formed by two electrons, 1 from each atom

Silicon (Si) is the dominant semiconductor material used in the electronics industry. In 1 m^3 of Si, there are $\sim 10^{28}$ atoms. Among these 10^{28} , there will be about 1.5×10^{16} **vacancies at room temperature**. This is known as the *intrinsic carrier concentration*: $n_i = 1.5 \times 10^{16}$ **electrons/m³**. This corresponds to **1 free electron for every 10^{12} atoms**.

For intrinsic Si, no. of electrons = no. of holes

Extrinsic semiconductors

Intrinsic semiconductors:

$$n_{\text{electrons}} = n_{\text{holes}} \text{ (equal concentrations)}$$

Extrinsic semiconductors:

Greater concentration of one type of carrier over the other

N-type semiconductor

$$n_{\text{electrons}} \gg n_{\text{holes}}$$

(Mostly negative charge carriers)

P-type semiconductor

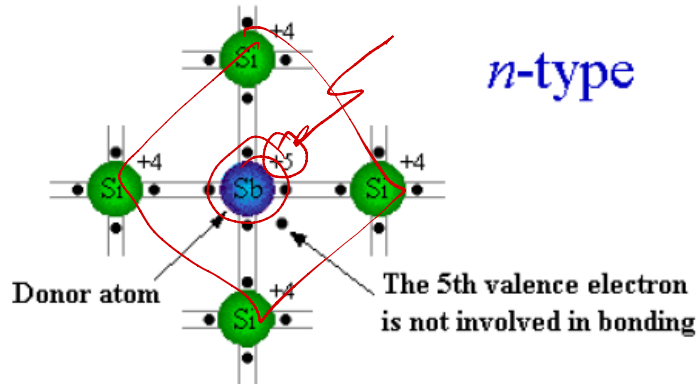
$$n_{\text{holes}} \gg n_{\text{electrons}}$$

(Mostly positive charge carriers)

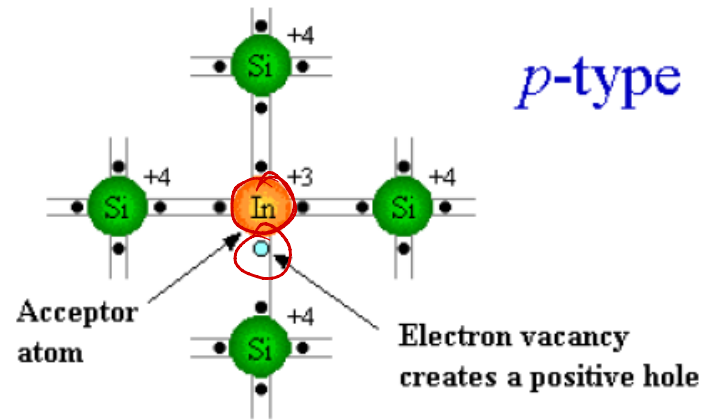
Doping to form extrinsic semiconductors

A semiconductor material that has been subjected to the doping process is called an extrinsic material. Both n-type and p-type materials are formed by adding a predetermined number of impurity atoms to a silicon base.

N-type extrinsic material



P-type extrinsic material



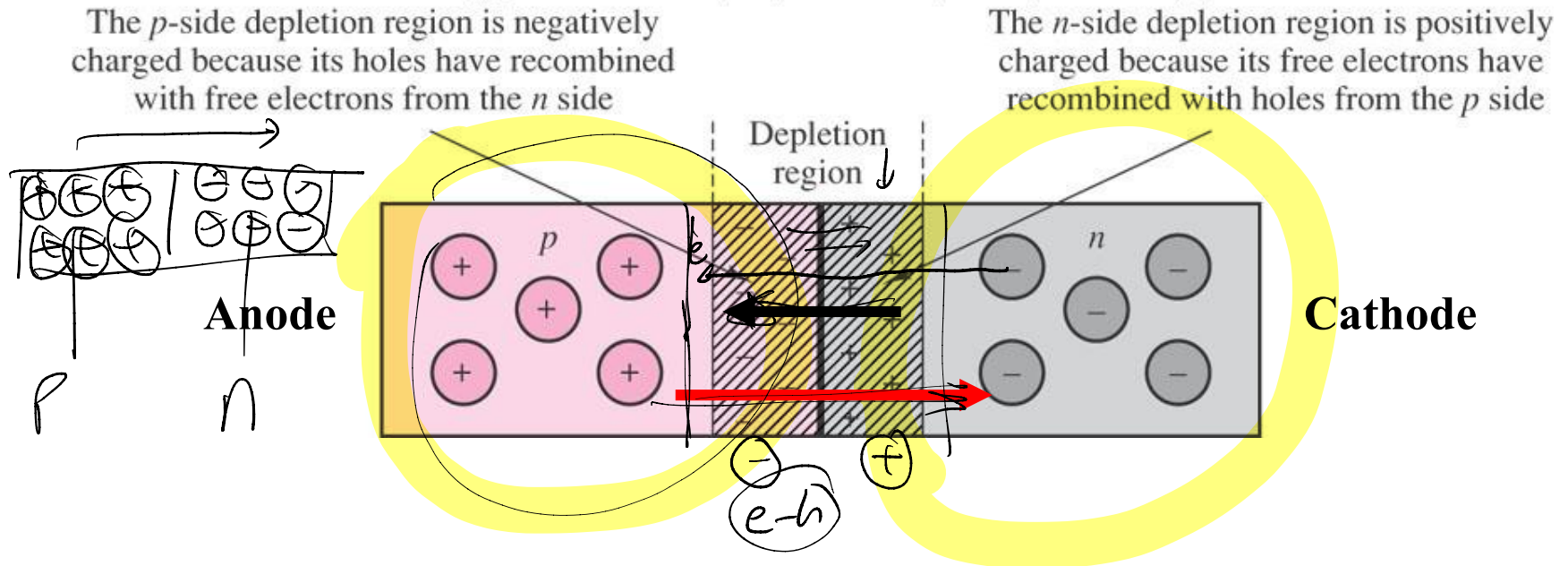
N-type material is created by introducing impurity elements that have five valence electrons. In an n-type material, **electrons are the majority carriers**.

P-type material is created by introducing impurity elements that have three valence electrons. In a p-type material, **holes are the majority carriers**.

This process is called **DOPING**

What does it make of?

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.



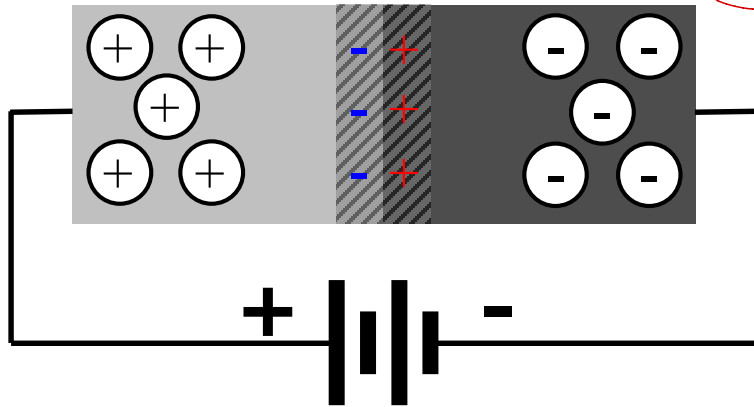
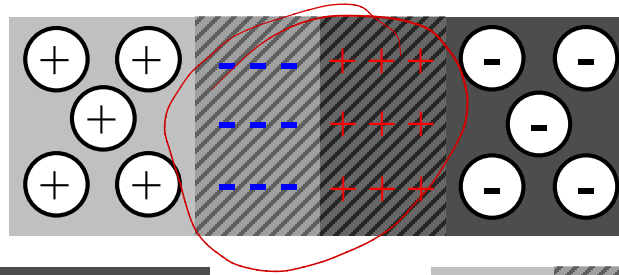
The pn junction forms the basis of the semiconductor diode.

There are no free carriers within the depletion region since the holes and electrons at the interface between the *p*-type and *n*-type recombine.

How does a Diode work?

When no voltage is applied across the diode

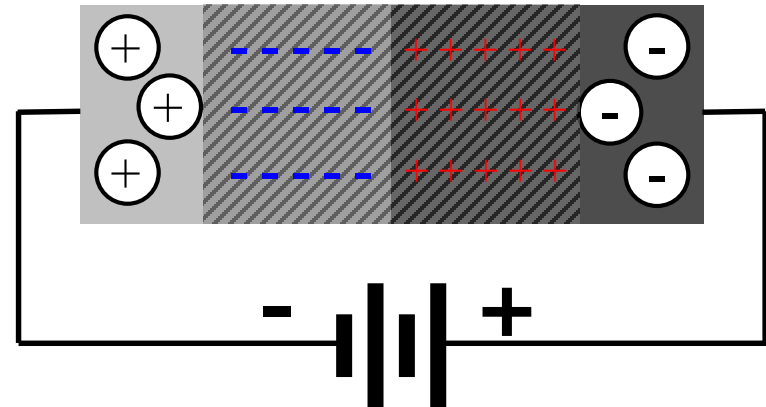
**Diode is not a linear device
which obeys ohm's law**



Forward biased:

Anode at a higher voltage than the cathode
Depletion width ↓, ↓ barrier for majority
carriers to move across the depletion region

Large conduction current



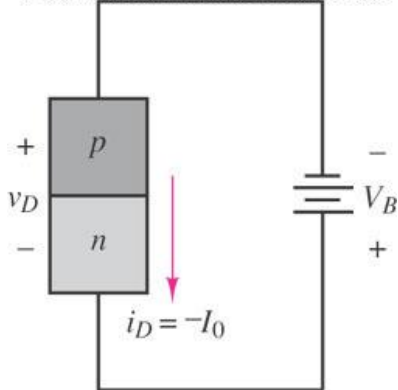
Reverse biased:

Anode at lower voltage than cathode
Depletion width ↑, ↑ barrier for majority
carriers to move across the depletion region

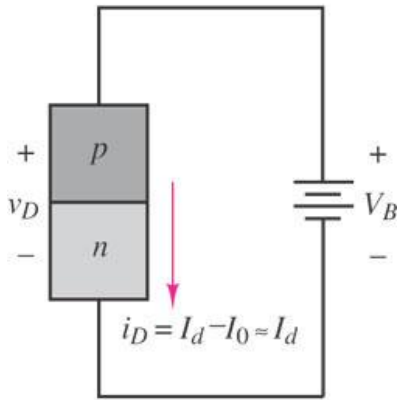
Very small leakage current

What is its electrical (V-I) characteristic?

Copyright © The McGraw-Hill Companies, Inc.
Permission required for reproduction or display.

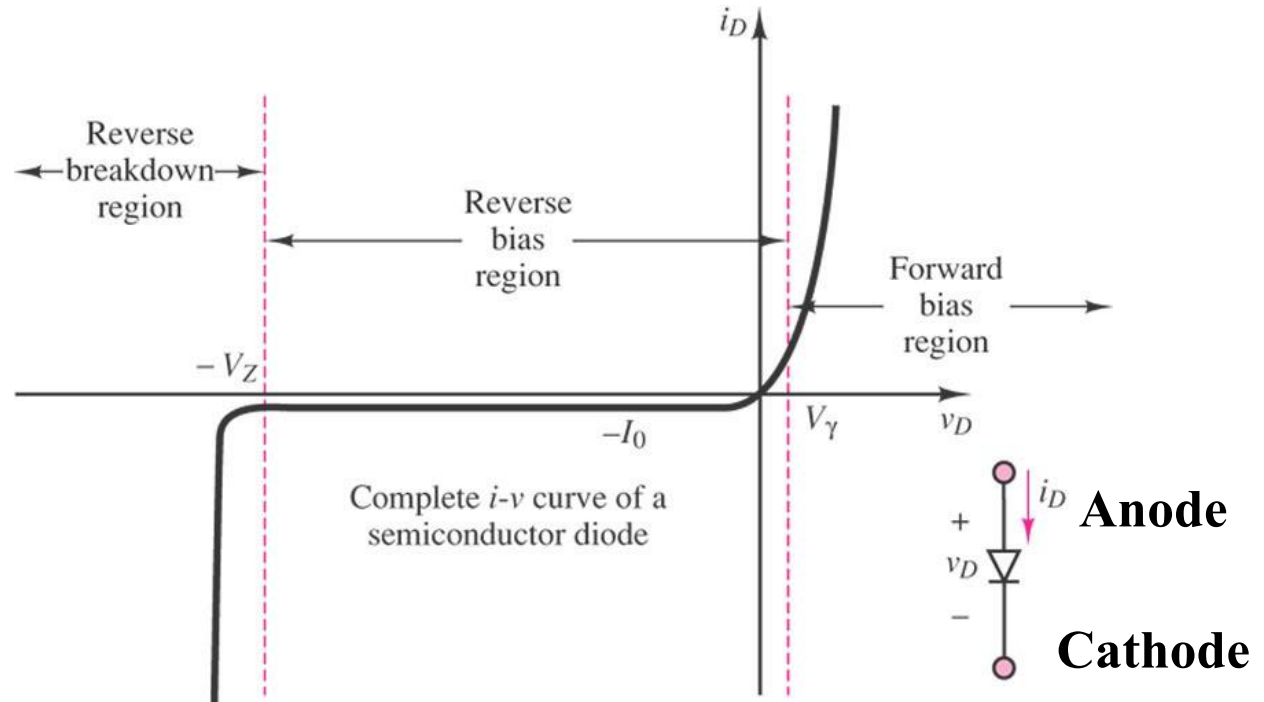


(a) Reverse-biased *pn* junction



(b) Forward-biased *pn* junction

Diode begins to conduct a significant amount of current: Voltage V_γ is typically around 0.7V



Shockley Diode Equation

Shockley equation:

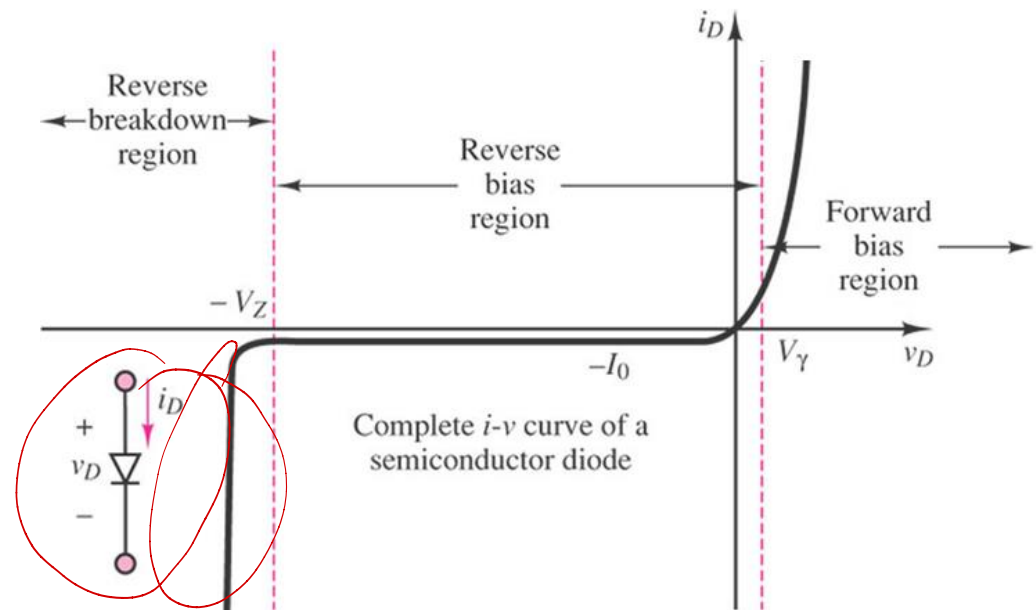
$$i_D = I_0 (e^{v_D/V_T} - 1), I_0 = \text{constant}, V_T = nkT/q$$

$k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant

$q = 1.60 \times 10^{-19}$ C is the magnitude of the electrical charge of an electron.

n = diode parameter, typically = 1

$V_T \sim 25$ mV at 300 K



Diode Example 1

At a temperature of 300K, a certain junction diode has $i_D = 0.1\text{mA}$ for $v_D = 0.6\text{V}$. Assume $V_T = 0.026\text{V}$. I_0 is the diode saturation current.

- 1) Find the value of the saturation current I_0 .
- 2) Find the percentage increase in i_D if v_D is increased from 0.6V to 0.8V

Given Shockley Diode equation: $i_D = I_0(e^{v_D/V_T} - 1)$

Working:

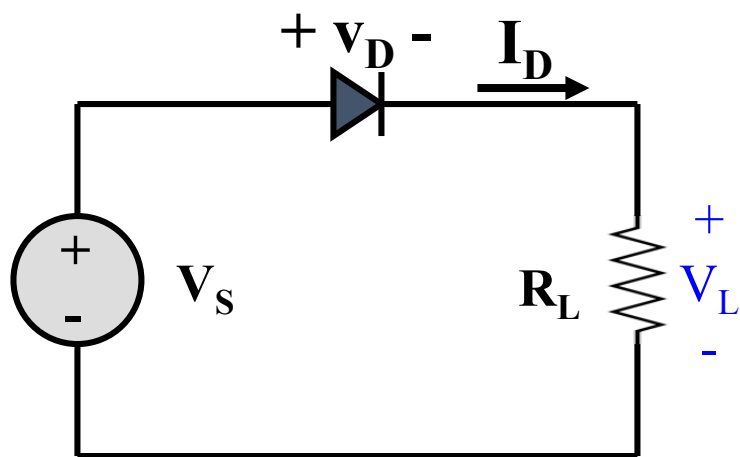
$$1) \quad I_0 = \frac{i_D}{(e^{v_D/V_T} - 1)} = \frac{0.0001}{(e^{0.6/0.026} - 1)} = 9.502 \times 10^{-14} \text{A}$$

$$\begin{aligned} i_{D1} &= I_0 e^{v_{D1}/V_T} \\ i_{D2} &= I_0 e^{v_{D2}/V_T} \end{aligned}$$

$$\begin{aligned} i_{D1} &= i_{D2} e^{\frac{v_{D2} - v_{D1}}{V_T}} \\ \frac{i_{D1}}{i_{D2}} &= e^{\frac{v_{D2} - v_{D1}}{V_T}} = e^{\frac{0.2}{0.026}} \end{aligned}$$

How to calculate a diode voltage and current in an electrical circuit?

Tedious: requires numerical methods



To find V_L where V_S and R_L are known,

First, apply KVL around the loop:

$$V_S = V_D + R_L I_D, \quad V_T \text{ and } R_L \text{ are known}$$

Then use the diode equation:

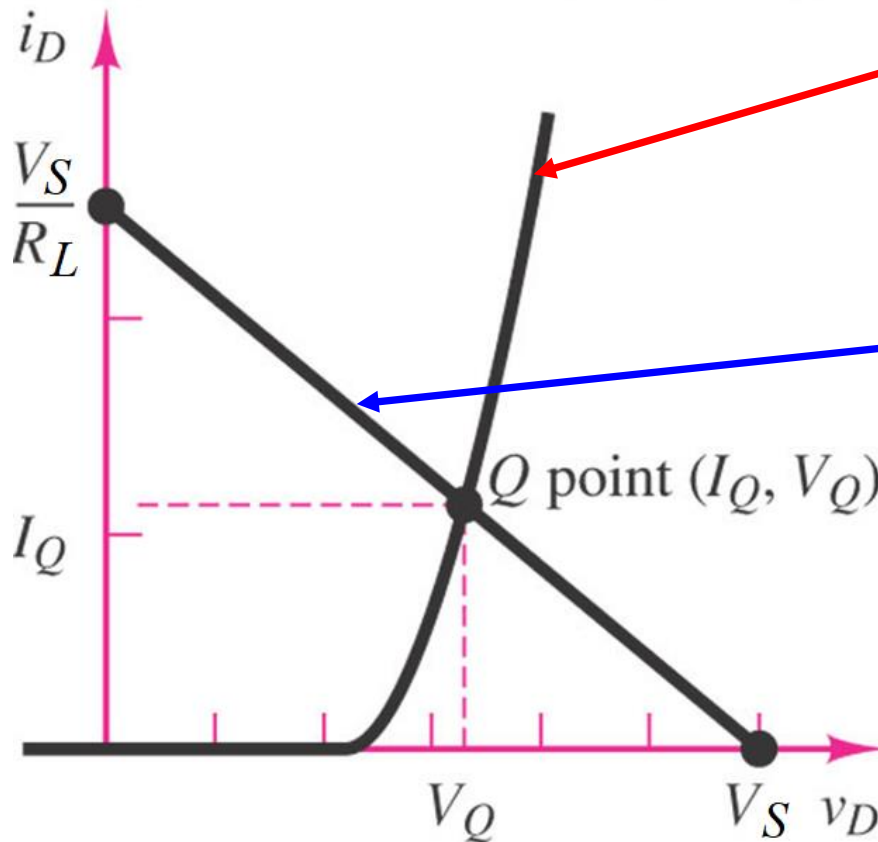
$$I_D = I_0 (e^{V_D/V_T} - 1), \quad I_0 = \text{constant}, \\ V_T = 26 \text{ mV at } T = 300\text{K}$$

$$V_S = V_D + R_L I_0 (e^{V_D/V_T} - 1)$$

We then need to solve these two simultaneous equations, which is not trivial. The other alternative is to use the graphical method to find the value of I_D and V_D (next slide)

Using graphical means to determine the Q point

The plot of diode current vs diode voltage



$$V_S = V_D + I_D R_S$$

From Shockley Equation

$$i_D = I_0(e^{v_D/V_S} - 1)$$

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

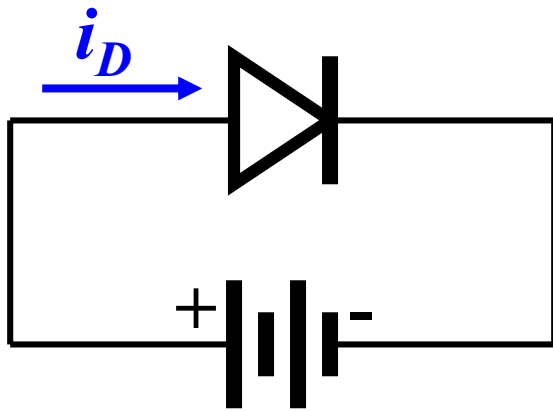
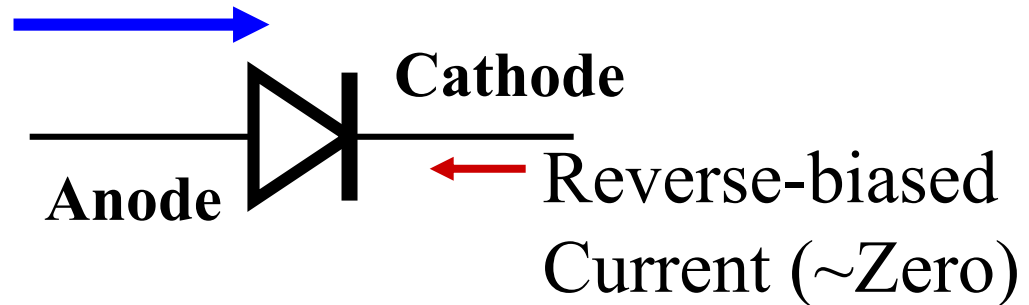
From KVL

$$i_D = -\frac{1}{R_L} v_D + \frac{V_S}{R_L}$$

The operating point is where the load line & I-V curve of the diode **intersect**

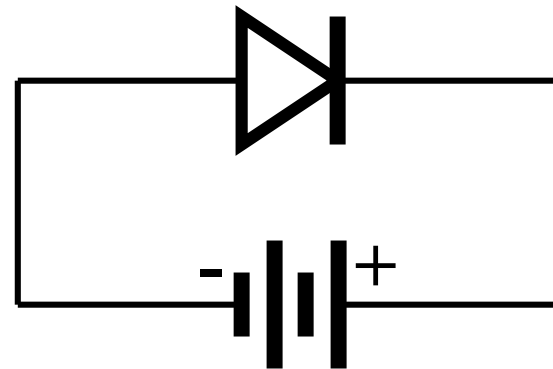
Diode Properties under large current

Forward-biased
Current (Large)



Forward Biased:

Diode conducts



Reverse Biased:

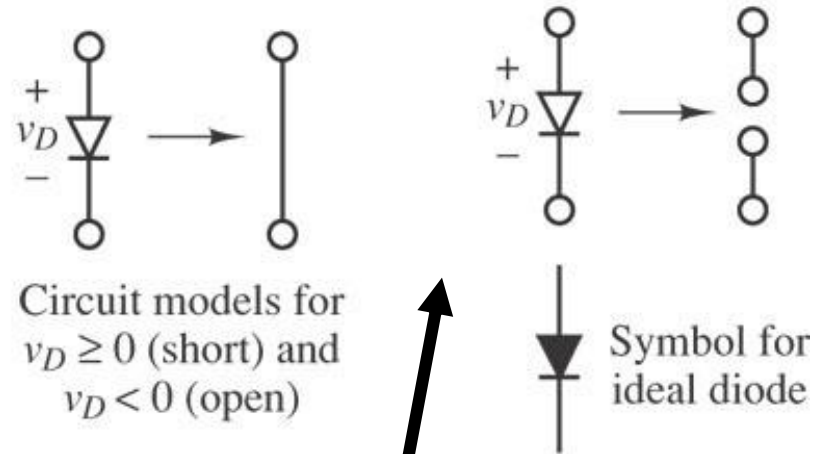
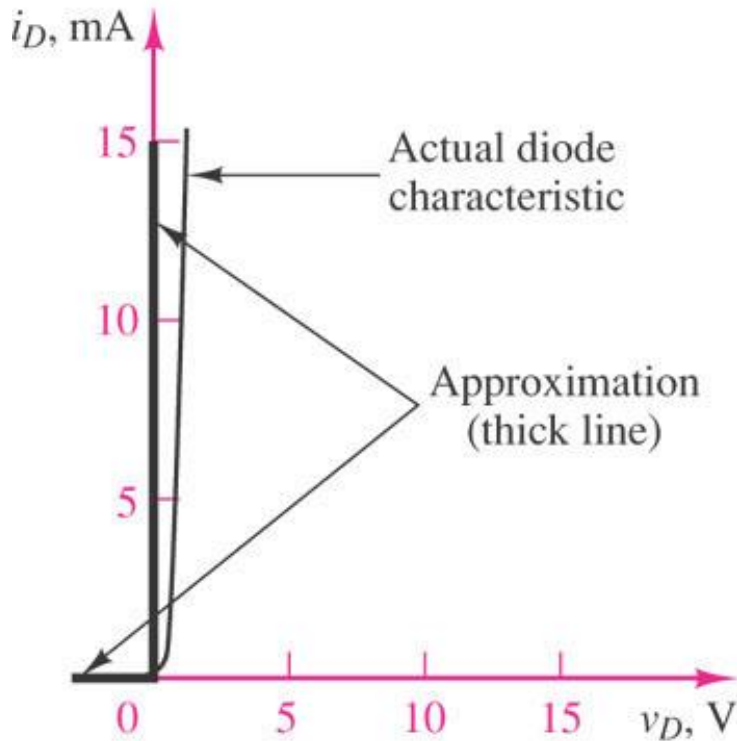
Little or no current

How to model a diode characteristic under large signal operation?

- 1) Large-signal models are a quick and fast alternative to analyze circuits with diodes
 - » Graphs (complicated with more components)
 - » Equations (write codes to solve)
- 2) Large signal models are **approximations**: describing the device behavior for large changes in voltages & currents
- 3) Two types of large signal models for this course (both based on a switch or ON/OFF concept):
 - » Ideal diode model
 - » Offset diode model

Ideal diode model

Copyright©The McGraw-Hill Companies, Inc. Permission required for reproduction or display.



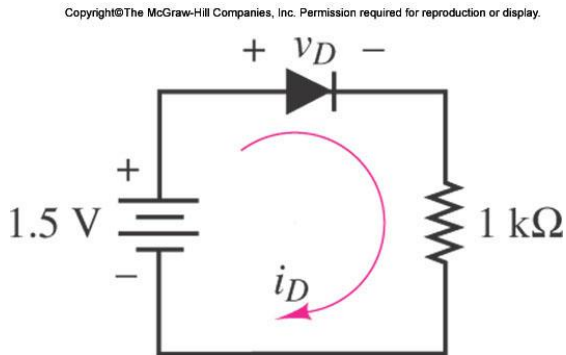
$v_D > 0$: Short circuit

$v_D < 0$: Open circuit

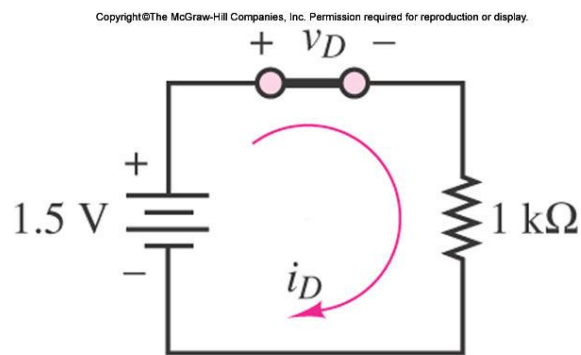
In other words, a diode is treated as a switch here

Ideal diode model

CASE 1

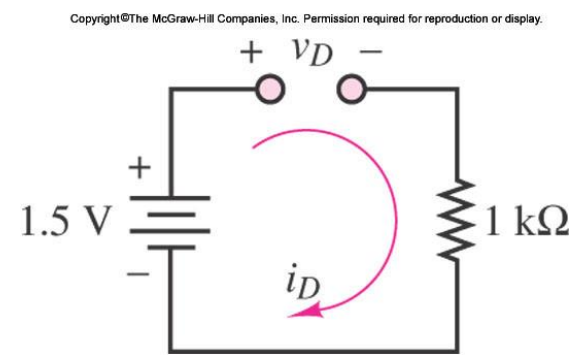


Circuit containing
ideal diode



Circuit assuming that the
ideal diode conducts

CASE 2



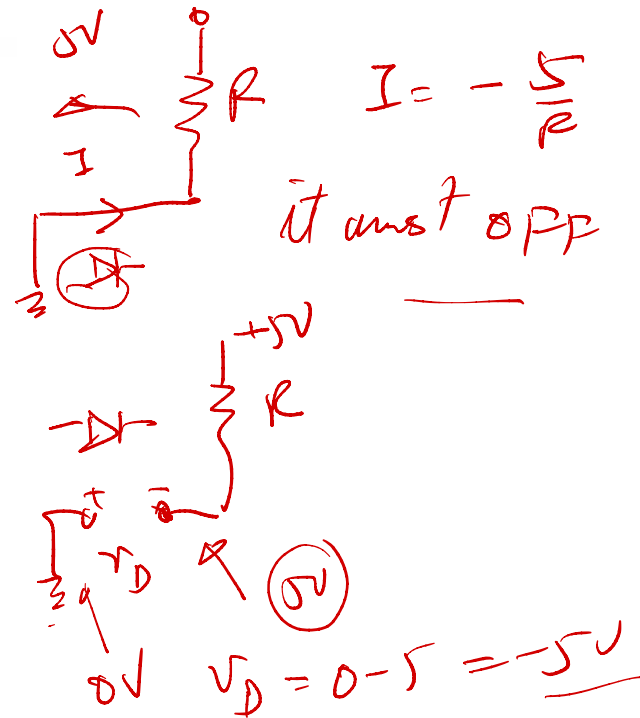
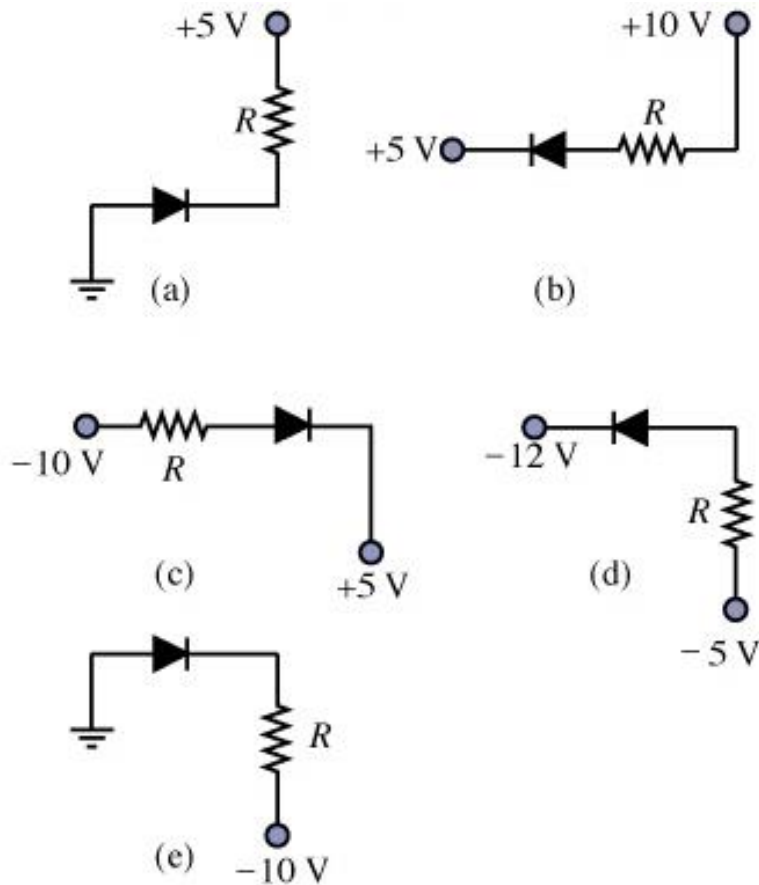
Circuit assuming that the
ideal diode does not conduct

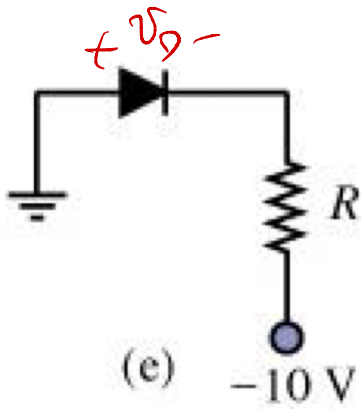
Case 1: Assuming the diode conducts and replacing it with a short circuit, we work out the direction of the current. We find that the diode current runs from the anode to the cathode. This is what we would expect if the diode was ON.

Case 2: Assuming the diode blocks and replacing it with an open circuit, we work out the voltage drop across the diode. We find that the voltage of the anode is higher than the cathode. This is contrary to what we would expect if the diode was OFF.

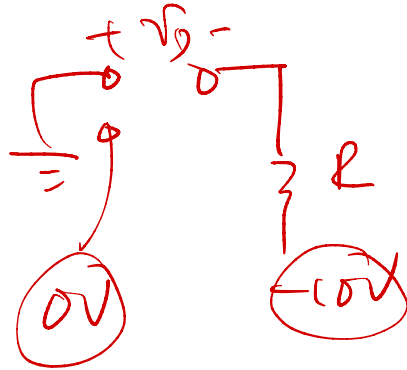
Ideal diode example 1

Determine which diodes are ON and which are OFF





assume the diode
is ~~OFF~~



$$v_D = 0 - (-10)$$

$$= \textcircled{10V}$$

the result contradict
to our assumption
 $\Rightarrow$ Diode is ON

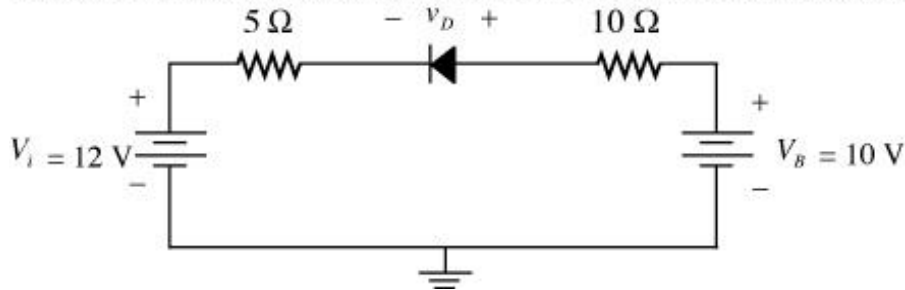
Ideal diode example 2

Problems 9.7 and 9.8

Determine whether the diode is conducting or not. Assume diode is ideal

Repeat for $V_i = 12\text{V}$ and $V_B = 15\text{V}$

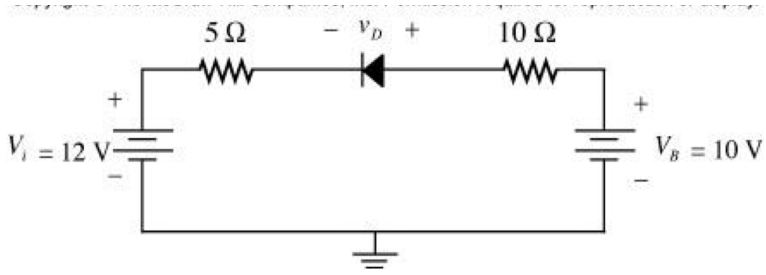
Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.



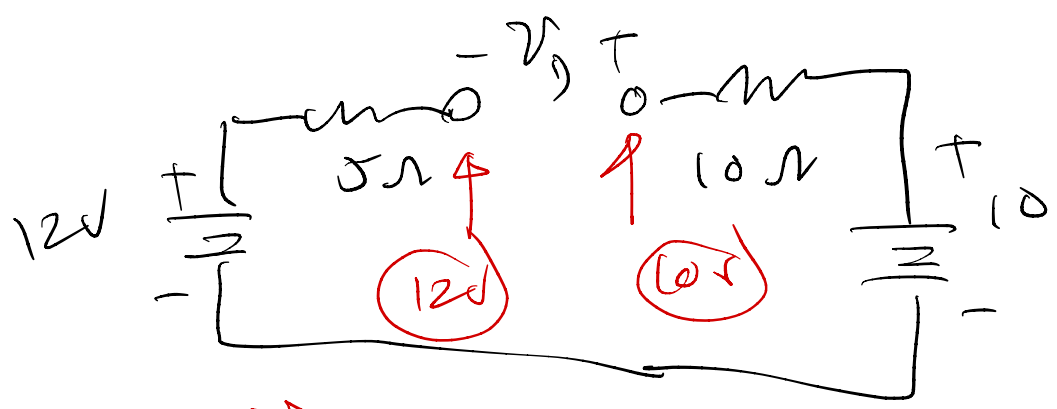
Case 1: Assume diode is ON: Replace with short circuit and find diode current direction
Diode confirmed as ON if diode flows from anode to cathode

Case 2: Assume diode is OFF: Replace with open circuit and find the voltage drop across diode

Diode confirmed as OFF if voltage drop from anode to cathode is negative



assume the diode is OFF



$$V_D = 10 - 12 = -2V$$

assumption is correct

the diode is OFF

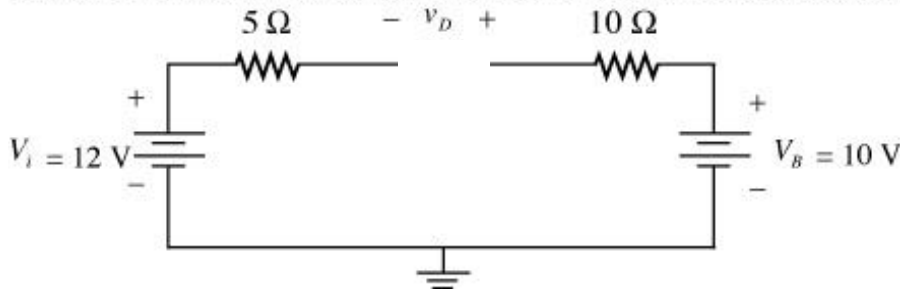
Ideal diode example 2 solution

Case 1: Assume diode is ON → Replace diode with short circuit

Diode current (I_D) = $(10-12)/(5+10) = -2/15$ A

→ Contrary to our assumption that the diode is ON

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

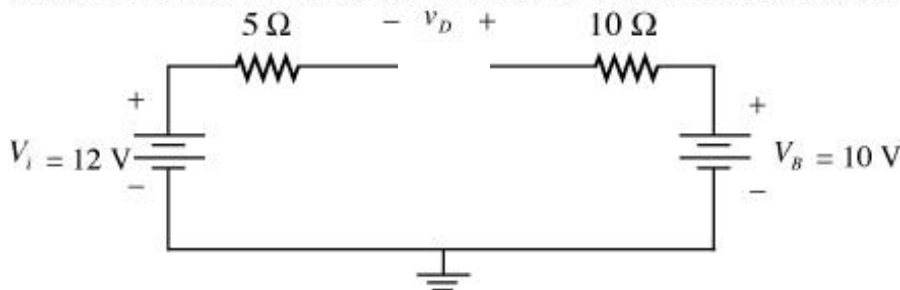


Case 2: Assume diode is OFF → Replace diode with open circuit

Diode voltage drop (V_D) = $10-12 = -2$ V

→ Confirms our assumption that the diode is OFF

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.



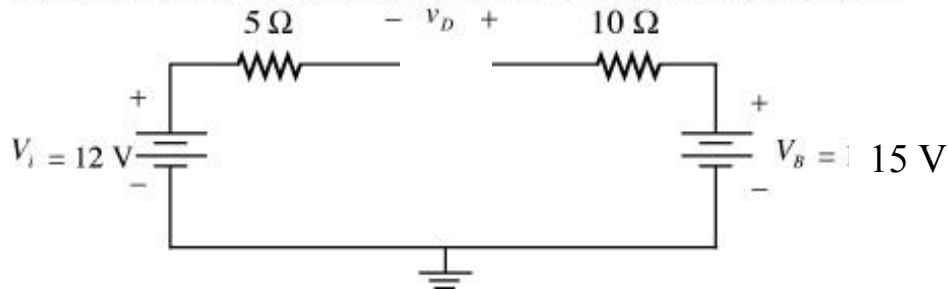
Ideal diode example 2 solution

Case 1: Assume diode is ON → Replace diode with short circuit

Diode current (I_D) = $(15-12)/(5+10) = 0.2$ A

→ Confirms our assumption that the diode is ON

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

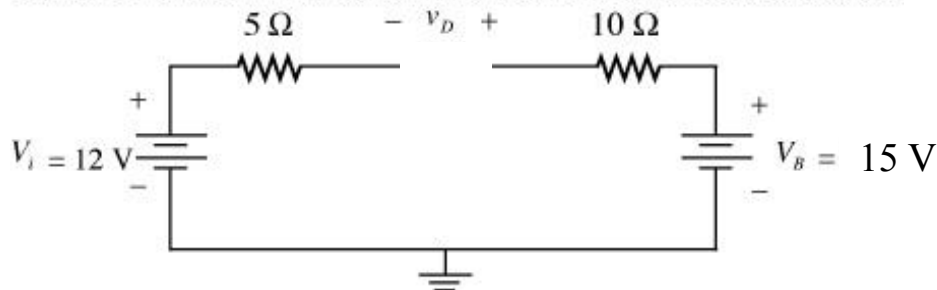


Case 2: Assume diode is OFF → Replace diode with open circuit

Diode voltage drop (V_D) = $15-12 = 3$ V

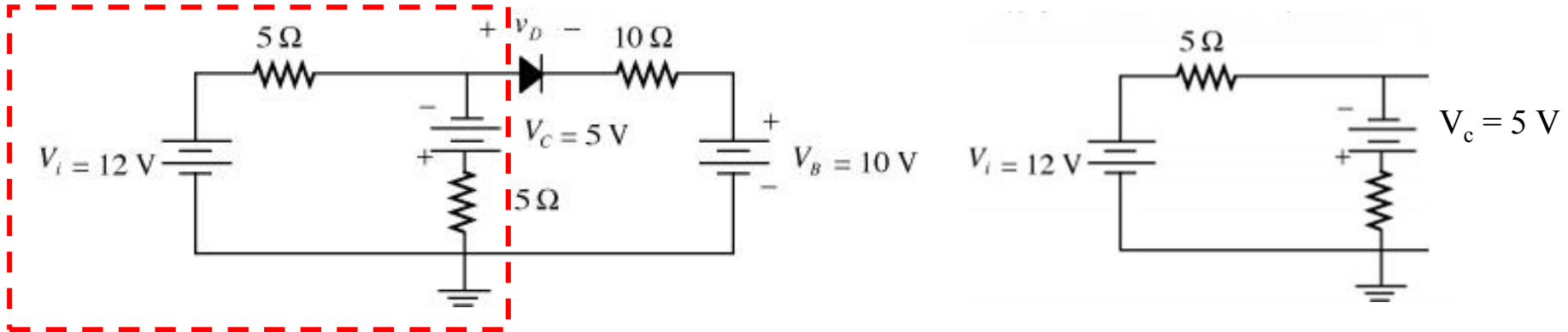
→ Contrary to our assumption that the diode is OFF

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

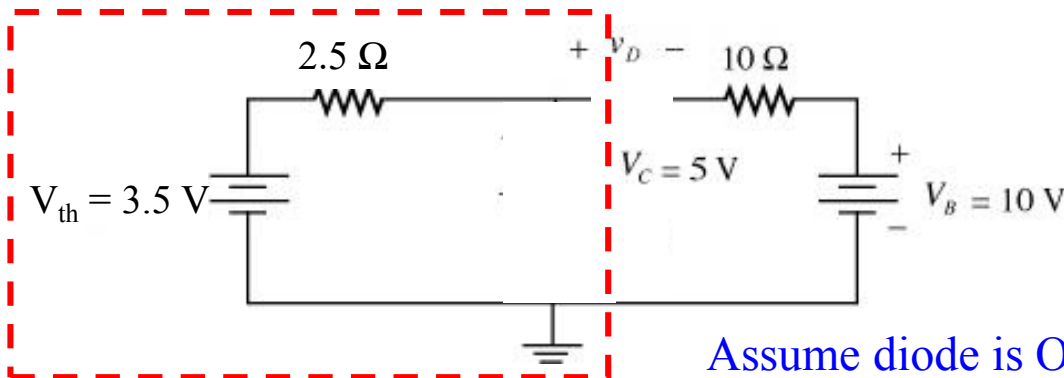


Ideal diode model example 3

Determine the state of the diode, assuming it is ideal.



Transform marked out a section of circuit to Thevenin



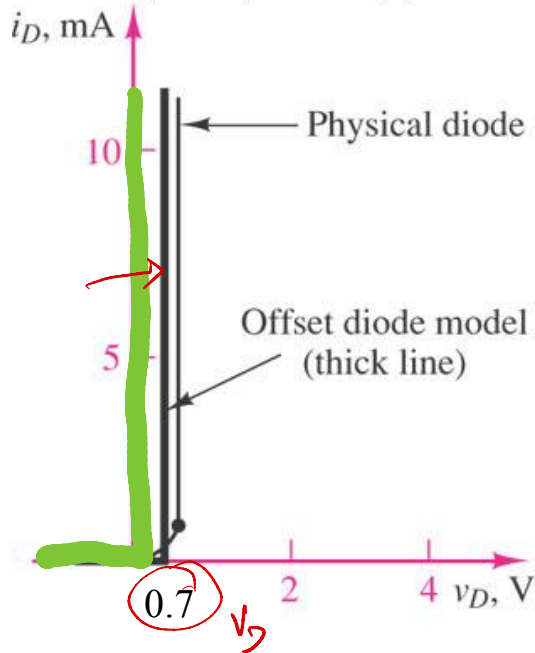
Assume diode is OFF $\rightarrow$ Replace diode with open circuit

Diode voltage drop (V_D) = $3.5 - 10 = -6.5\text{ V}$

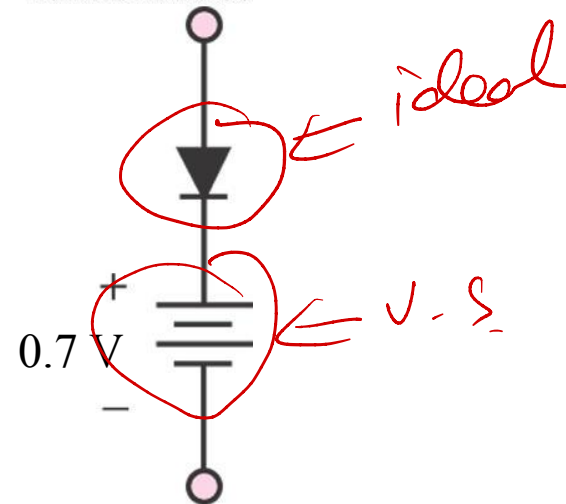
$\rightarrow$ Confirms diode is OFF

Offset diode model

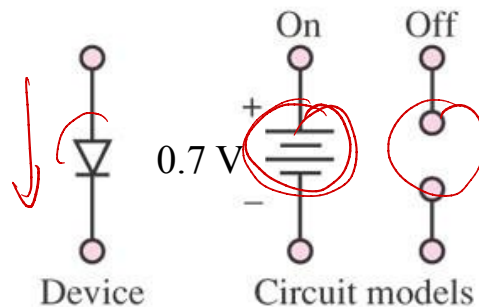
Copyright©The McGraw-Hill Companies, Inc.
Permission required for reproduction or display.



Copyright©The McGraw-Hill Companies, Inc. Permission required for reproduction or display.



V_γ is typically used to denote the offset voltage



$$v_D \geq 0.7 \text{ V}$$

Diode $\rightarrow$ 0.7 V battery

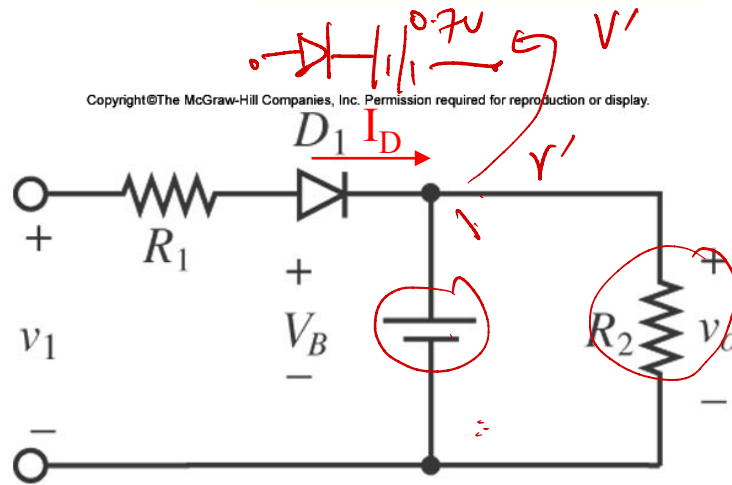
$$v_D < 0.7 \text{ V}$$

Diode $\rightarrow$ open circuit

Offset model example 1

Determine the state of the diode assuming it has a turn on voltage (V_γ) of 0.7 V and given that $V_1 = 5\text{V}$, $V_B = 2\text{V}$, $R_1 = 1\text{ k}\Omega$, $R_2 = 500\ \Omega$.

What is the lowest value of V_1 for the diode to turn on?



Work with assumption that diode is ON:

→ Find the direction and value of I_D

→ $V_1 = I_D \cdot R_1 + V_\gamma + V_B$

→ $I_D = (5 - 2.7)/1\text{k} = 2.3\text{ mA}$

→ Confirms that diode is ON

$$V_1 \geq 0.7 + V_B$$

$$= 0.7 + 2 = 2.7 \checkmark$$

Lowest value of V_1 for diode to be on:

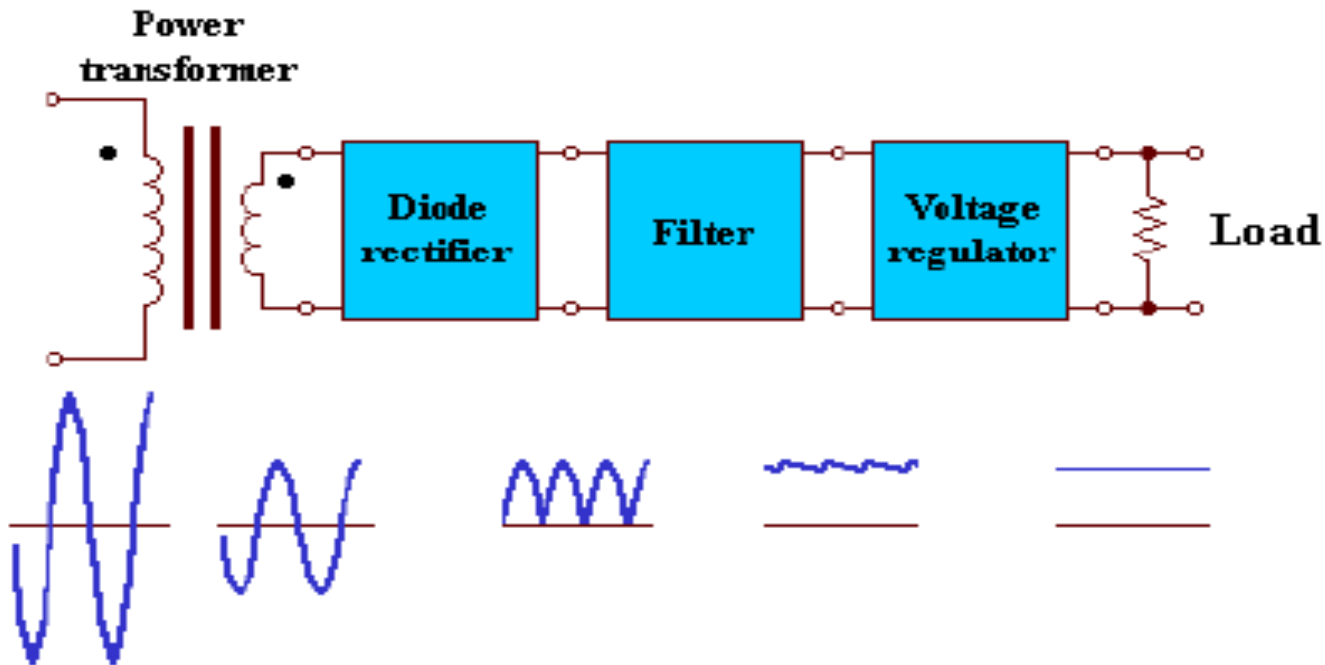
$$I_D = (V_1 - V_\gamma - V_B)/R_1 = (V_1 - 2.7)/1\text{k}$$

For I_D to be positive → $V_1 > 2.7\text{ V}$

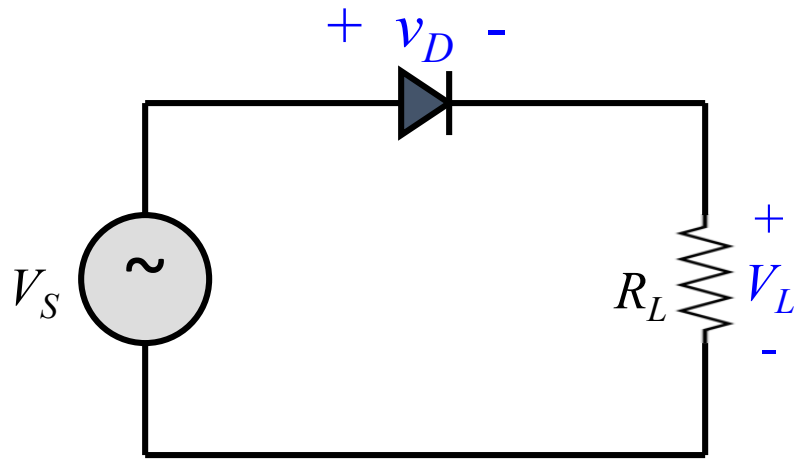
What is its applications?

Power Regulator

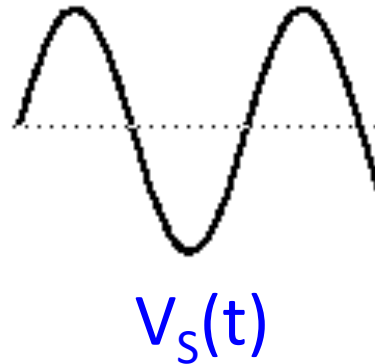
One common application of diodes is rectification. In rectification, an AC sinusoidal source is converted to a unidirectional output which is further filtered and regulated to give a steady DC output.



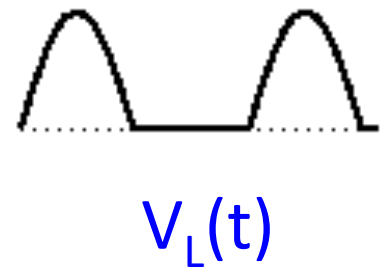
How a diode rectifies a AC to DC?



Bi-directional input



Uni-directional output converted

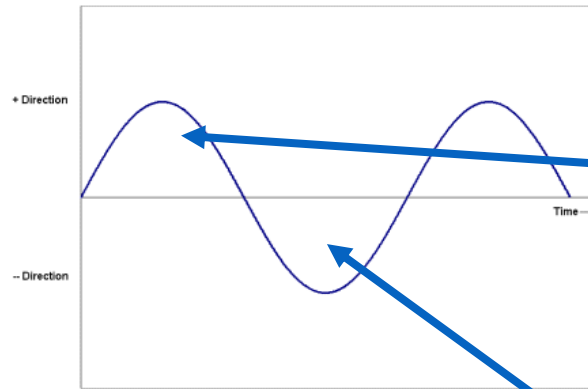
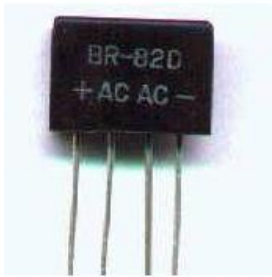


Circuit conducts for only half a cycle

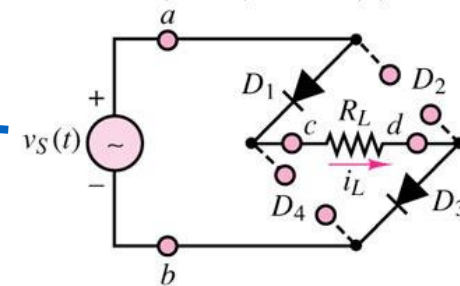
Half wave rectifier → **Not efficient !!**

Full-Wave Rectifier - Bridge

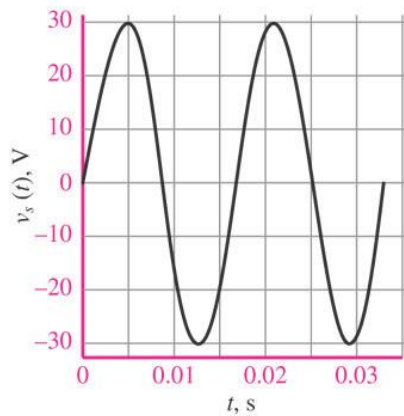
Comprises 2 sets of diode pairs
Each pair conducts in turn on each half-cycle



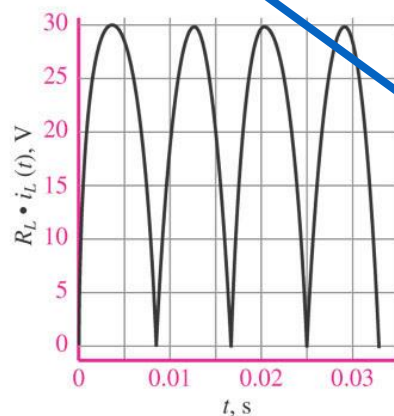
Copyright © The McGraw-Hill Companies, Inc.
Permission required for reproduction or display.



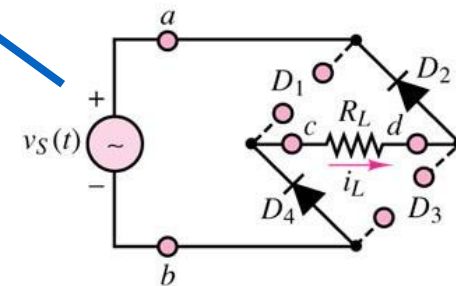
During the positive half-cycle of $v_S(t)$, D_1 and D_3 are forward-biased and $i_L = v_S(t)/R_L$ (ideal diodes).



(a)



(b)



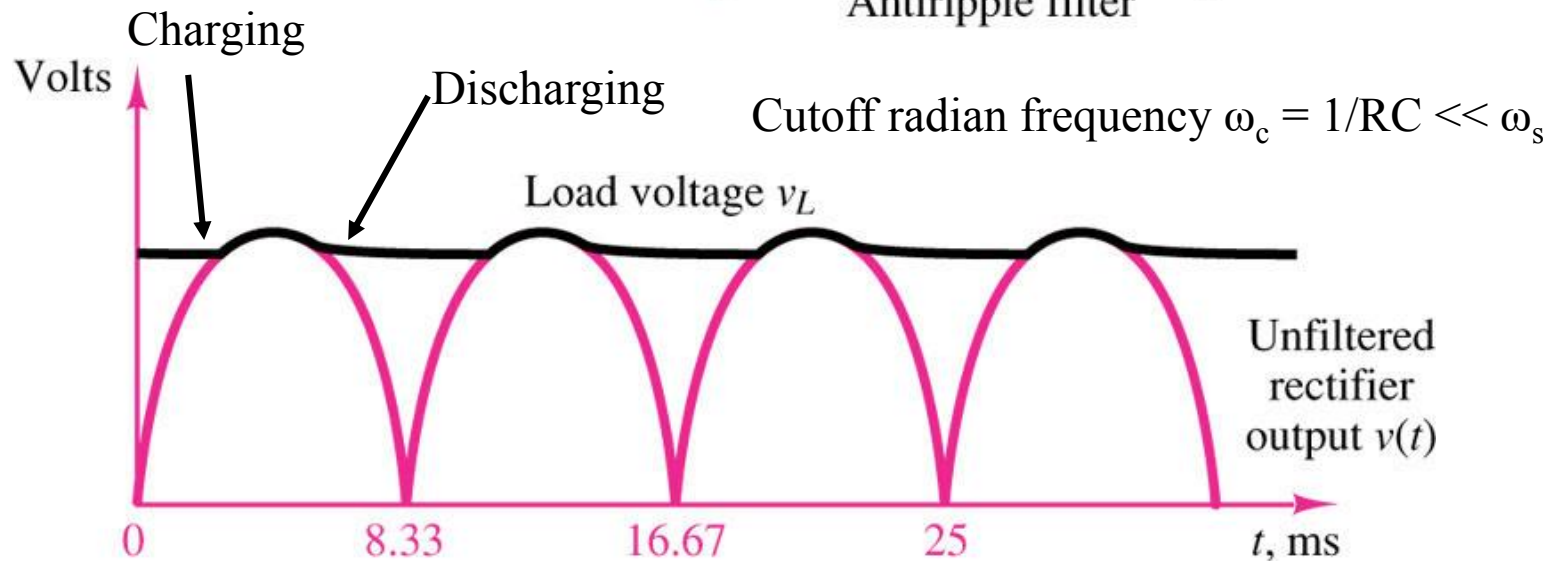
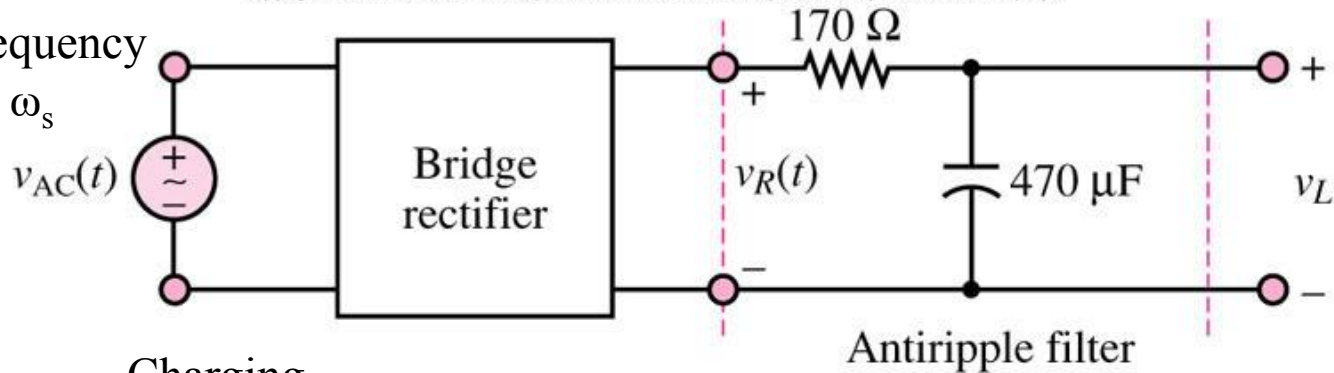
During the negative half-cycle of $v_S(t)$, D_2 and D_4 are forward-biased and $i_L = -v_S(t)/R_L$ (ideal diodes).

Ripple filter

Anti-ripple filter is used to smoothen out the rectifier output

Copyright©The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Radian frequency
of source: ω_s

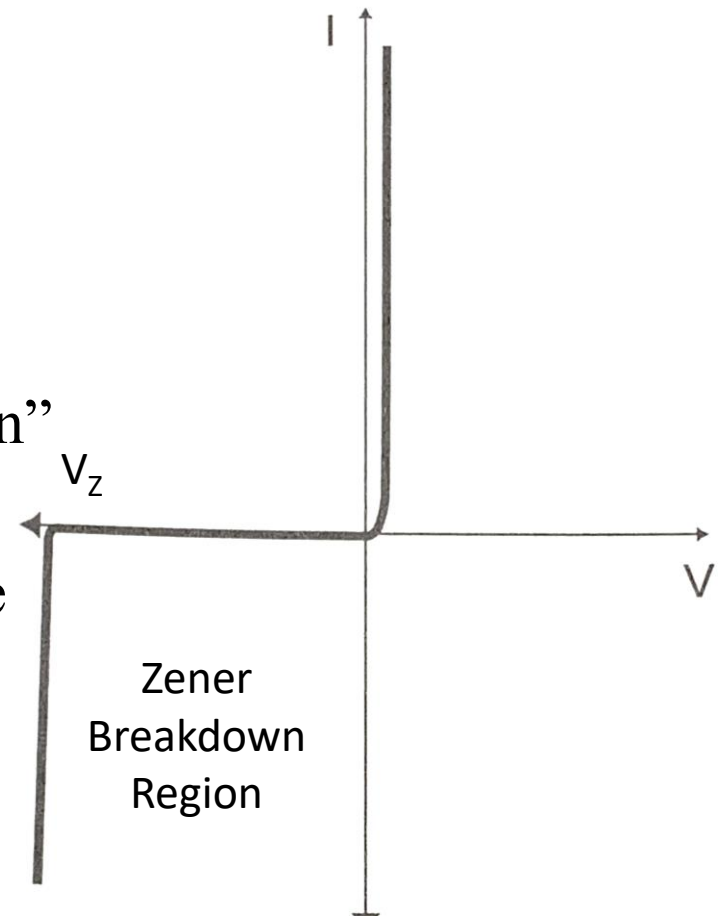


Zener diode – a special type of diode



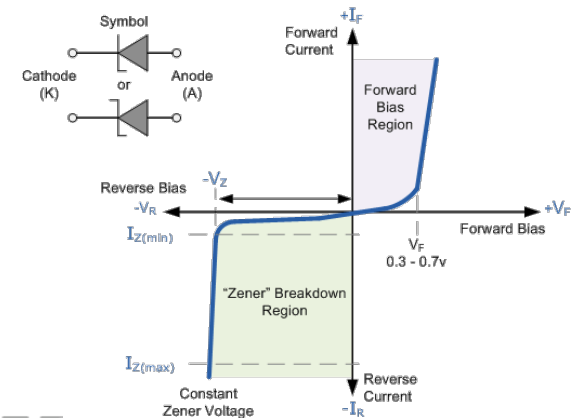
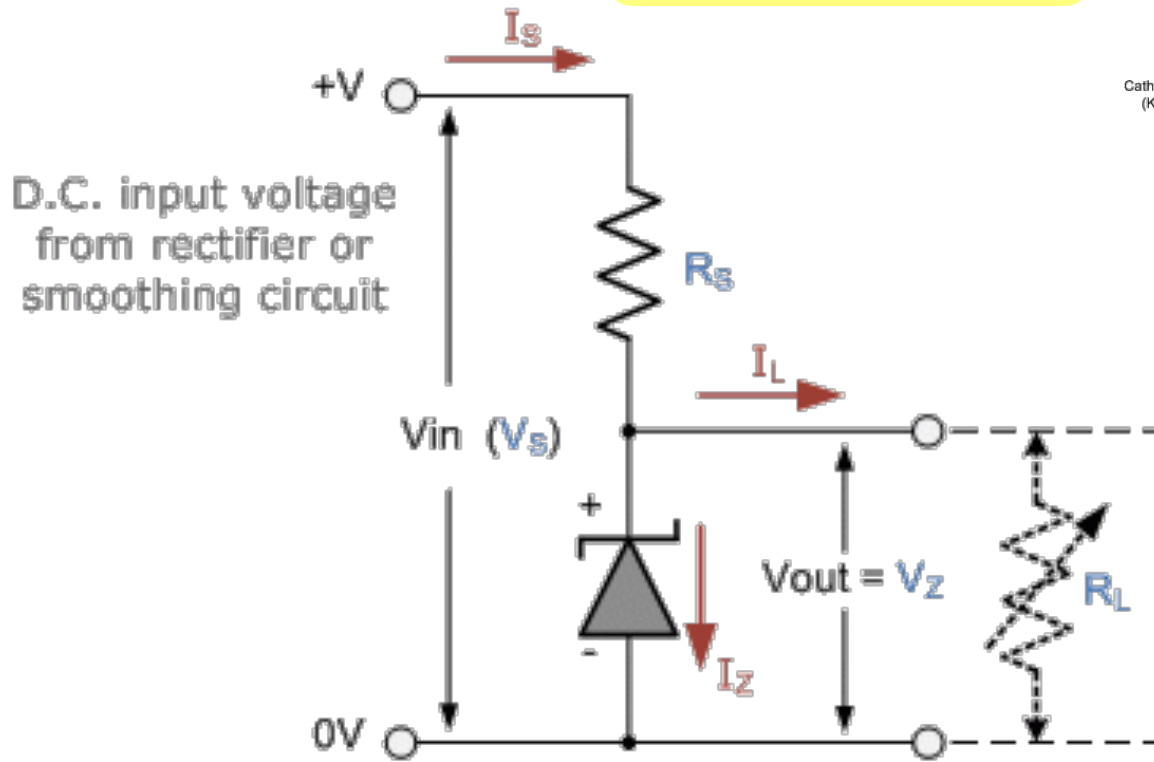
- Zener diode “Avalanche Breakdown”

- ➔ Low breakdown voltage V_Z
- ➔ Conduct with very small resistance
 - ➔ Steep I-V curve



Zener Diode as Voltage Regulator

- The Zener diode will control the current I_Z so as to keep I_L constant irrespective to a change in R_L .
- Maximum of I_Z is limited by the diode power rating



https://www.electronics-tutorials.ws/diode/diode_7.html

Summary

- 1) Free carriers are required for conduction
- 2) Positively and negatively charged free carriers can be engineered in semiconductors
- 3) A diode is a nonlinear device that we can model as an approximation as either conducting or blocking using large-signal models
- 4) Large signal diode models an approximation
 - » Ideal: Diode conducts with 0V offset across the diode
 - » Offset: Conduction results in a small offset voltage
- 5) One of the most important applications of diodes is a rectifier.

Reference: A 12min summary on diode: https://youtu.be/Fwj_d3uO5g8