EE/COE 152: Basic Electronics

Lecture 3

A.S Agbemenu

https://sites.google.com/site/agbemenu/courses/ee-coe-152

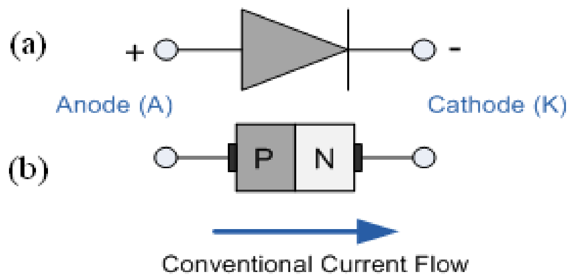
Books:
Microelcetronic Circuit Design (Jaeger/Blalock)
Microelectronic Circuits (Sedra/Smith)

Outline

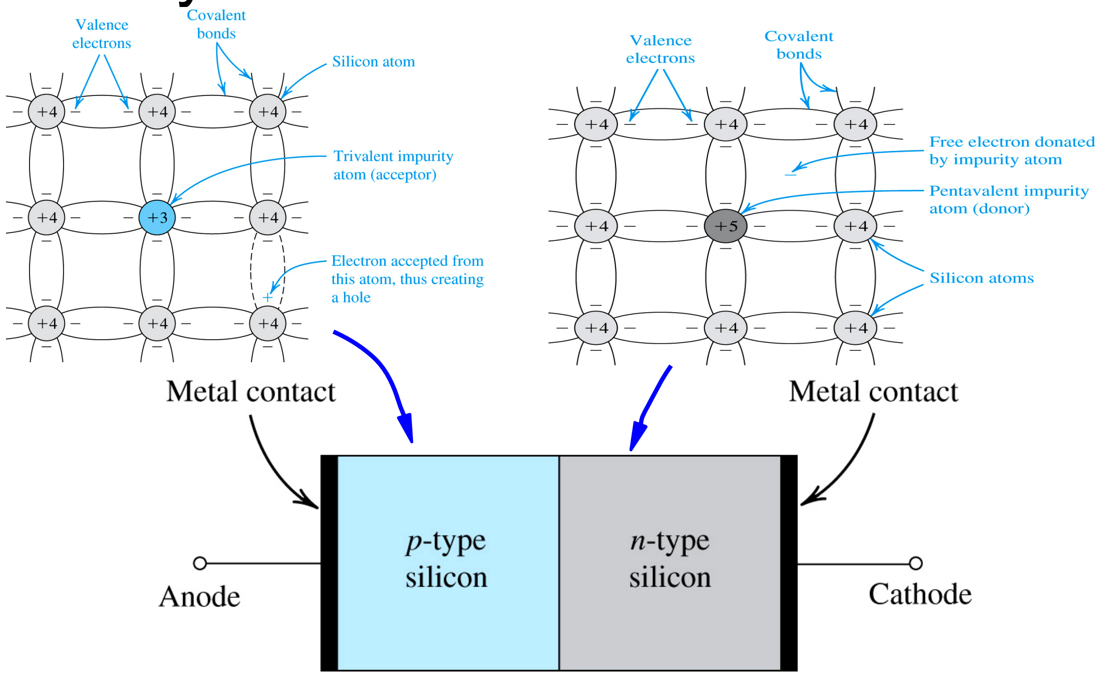
- PN Junction
- Diode Operation Modes
- Diode Models
- Diode Circuit Analysis
- Rectifier Circuits

PN Junction

- A PN junction is formed when a P-type (acceptor) semiconductor is joined to a N-type (donor) semiconductor such that the crystal structure remains continuous at the boundary
- This type of semiconductor configuration is call a ***diode***

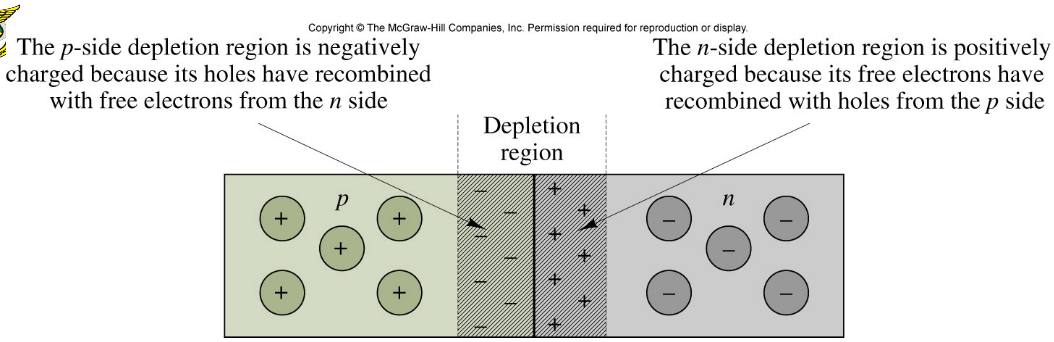


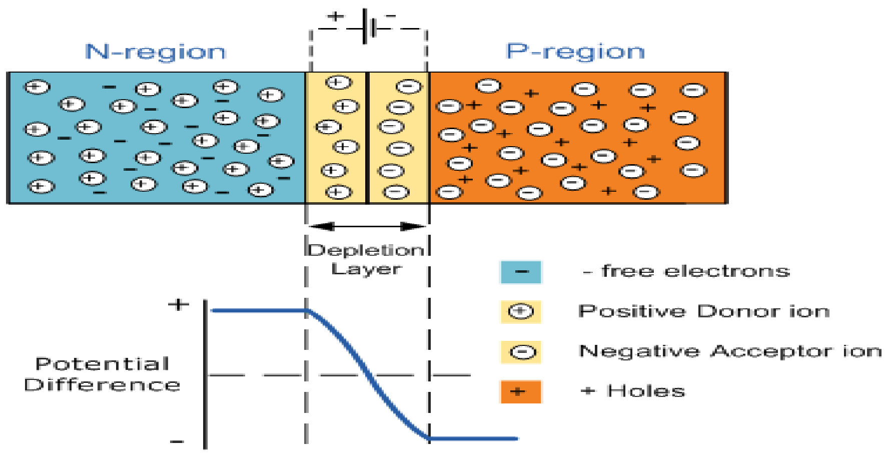
Physical Structure of the Diode



The PN Characteristics

- Electrons diffuse from the n-region junction to the p-region junction
- This diffusion created negative ions at the p-side of the junction and positive ions at the n-side of the junction
- Enough potential is built up to prevent any further diffusion of charge carriers
- This potential is ***Barrier/Junction Potential*** and the charged region ***Depletion region/layer***



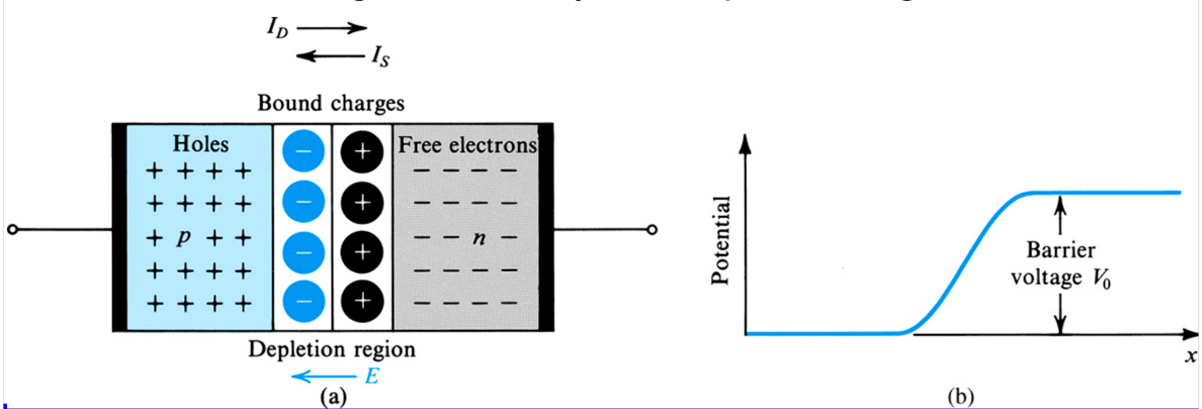


The Diode

- The diode operates in three modes
  - No Bias Mode
    - When no external voltage is applied to the terminals
  - Forward Bias Mode
    - When the terminals are connected such that the positive terminal is connected to the P-region and the negative terminal is connected to the N-region
  - Reverse Bias Mode
    - When the negative terminal is connected to the P-region and the positive terminal to the N-region

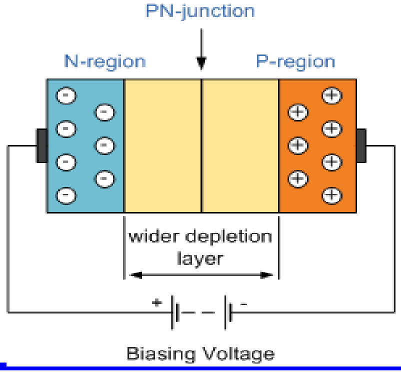
No Bias Mode

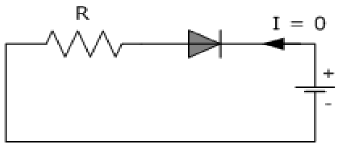
- Majority carriers diffuse into other region causing diffusion current, I_D
- Thermally generated minority charge carriers drift (generate drift current, I_s) across the junction due to electric field generated by the depletion region.



Reverse Bias Mode

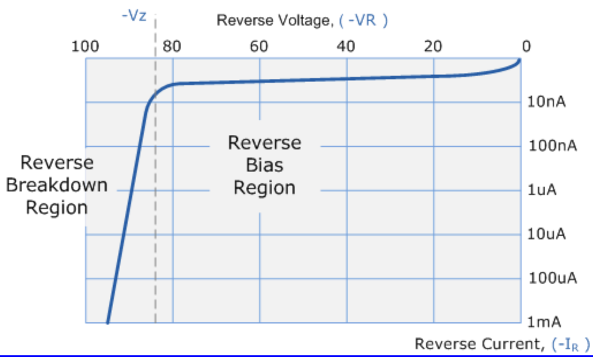
- In this mode the junction potential is effectively reinforced widening the depletion layer
- Free electrons from the n-region are attracted towards the positive terminal and electrons from the negative terminal enter the p-region widening the depletion layer





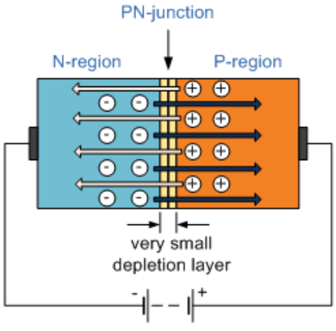
Reverse Bias Mode

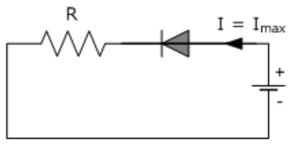
- In reverse bias mode a small ***leakage current*** flows through the junction
- Increasing the reverse voltage sufficiently will overheat the junction. This voltage is the ***breakdown voltage***
- The thermal energy created large electron-hole pair causing large currents to flow in a phenomenon called ***avalanche breakdown***



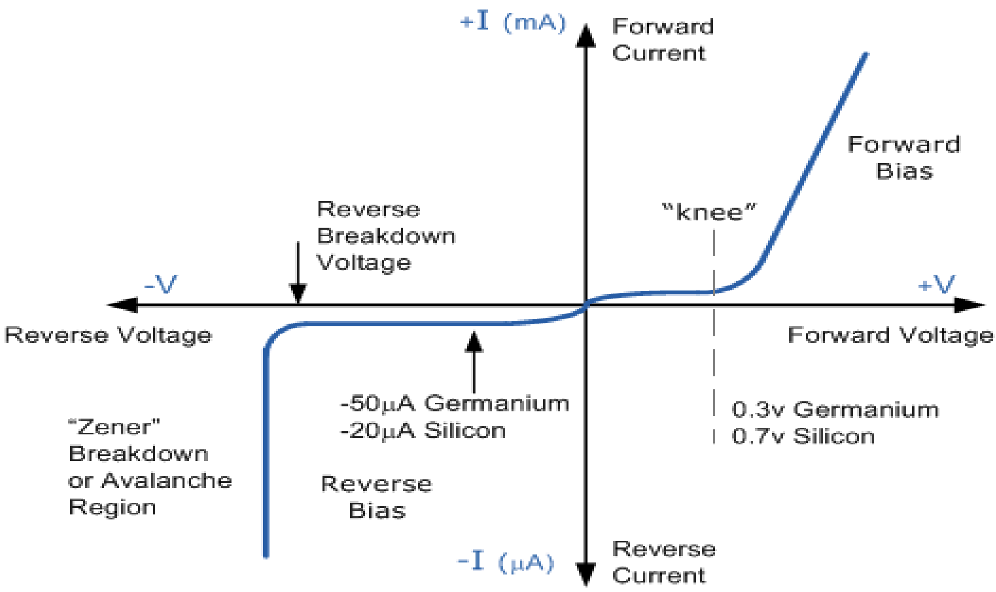
Forward Bias Mode

- In this mode, the electric filed is applied in the opposite direction to the barrier potential which results in the depletion layer becoming very thin
- When the applied voltage is greater than the barrier potential(*0.7V* for silicon and *0.3V* for germanium) , the diode starts conducting



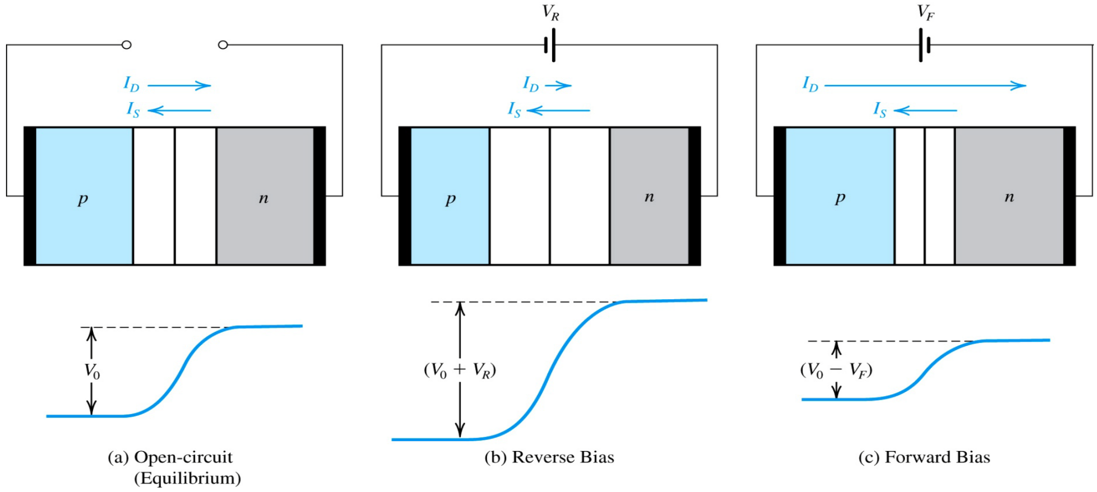


Diode Characteristics Curve



I-V characteristic curve of a diode

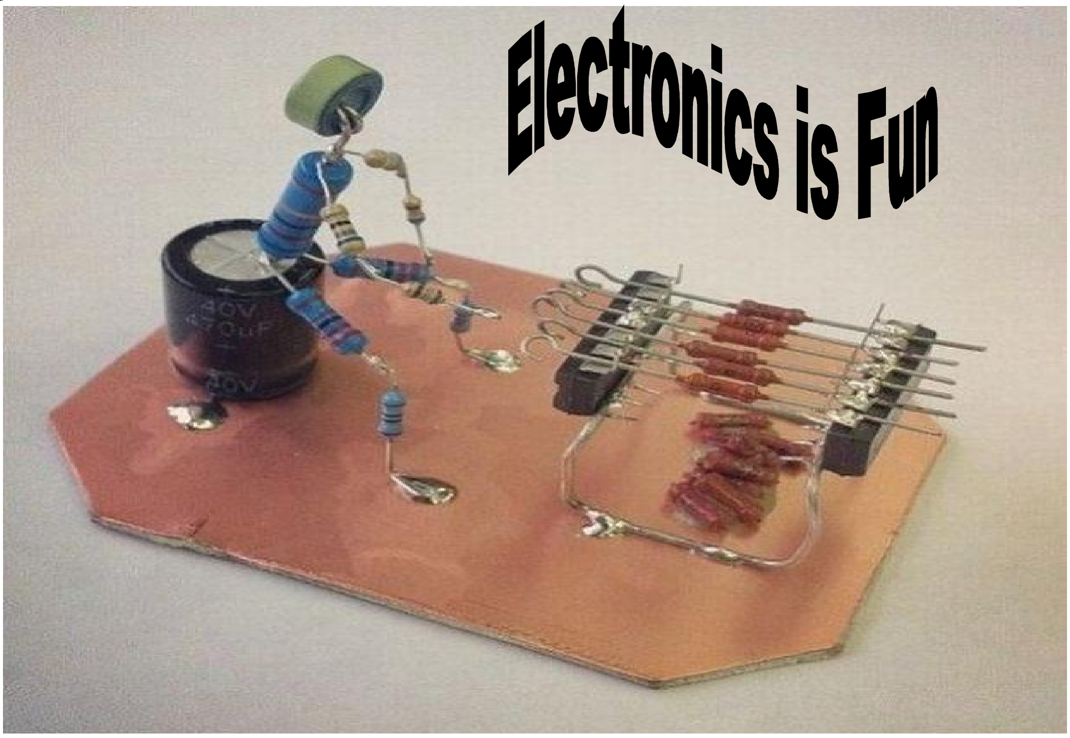
Generalized Diode Operation



Open Circuit, $I_D = I_S$

Reverse Biased, $I_D < I_S$

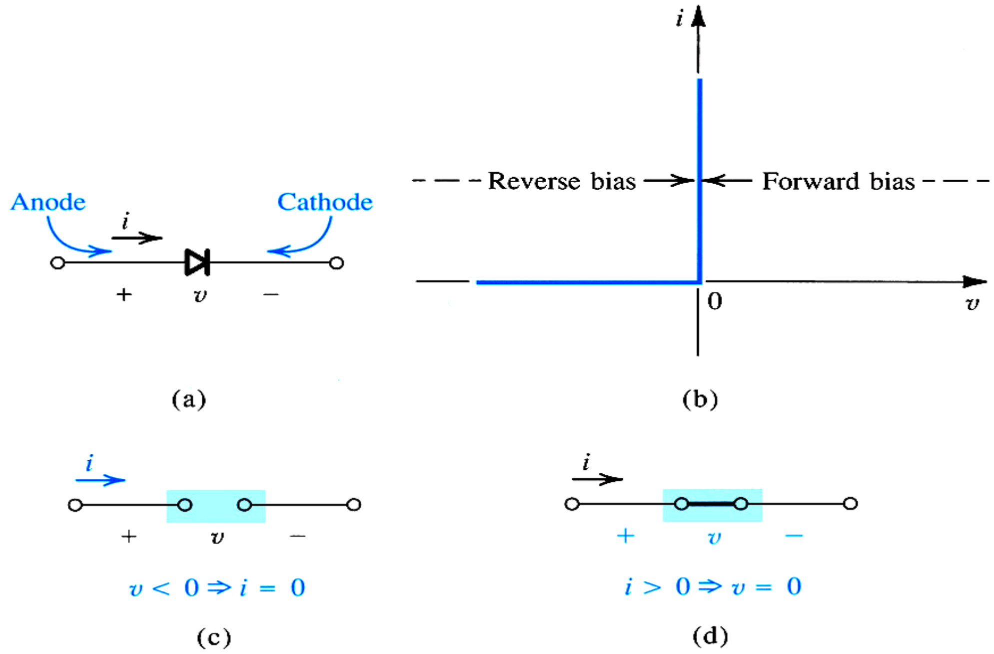
Forward Biased, $I_D >> I_S$



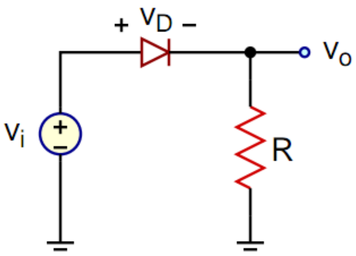
Diode Models

- In the forward bias mode, the diode can be modeled with
  - Ideal Model
    - The diode is modeled as a switch with no resistance
  - Constant Voltage Drop Model
    - The diode is modeled as having a constant voltage drop after which it behave as a switch
  - Exponential *I-V* Model
    - The diode equation defines the operation of the diode

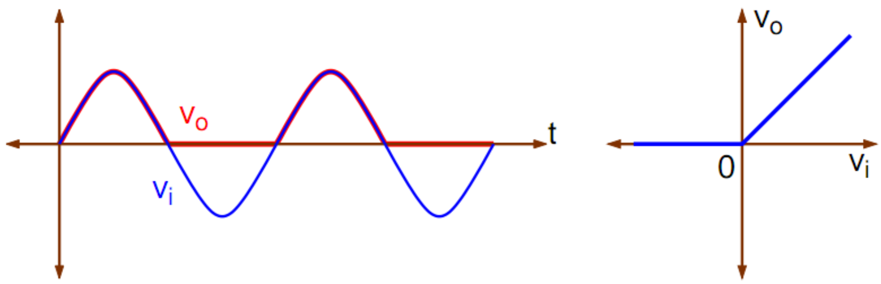
Ideal Diode Model



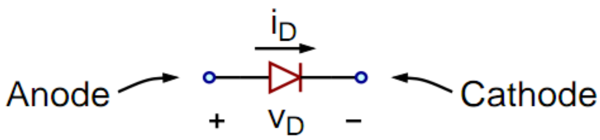
Ideal Diode Model

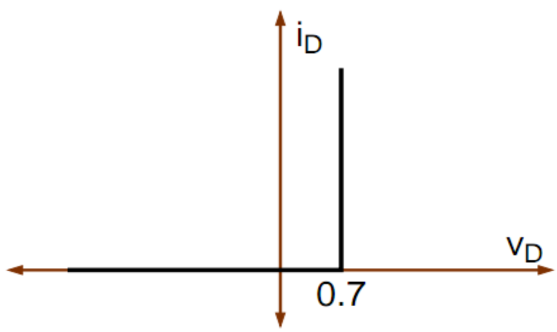


Diode does not drop any voltage across the terminal



Constant Voltage Drop Model

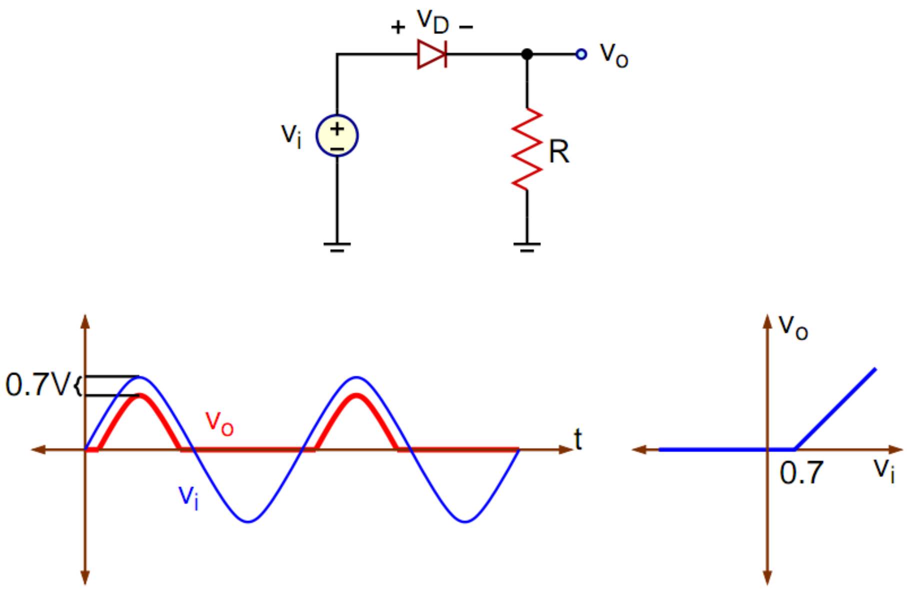




$$v_D < 0.7 \quad \Rightarrow \quad i_D = 0$$

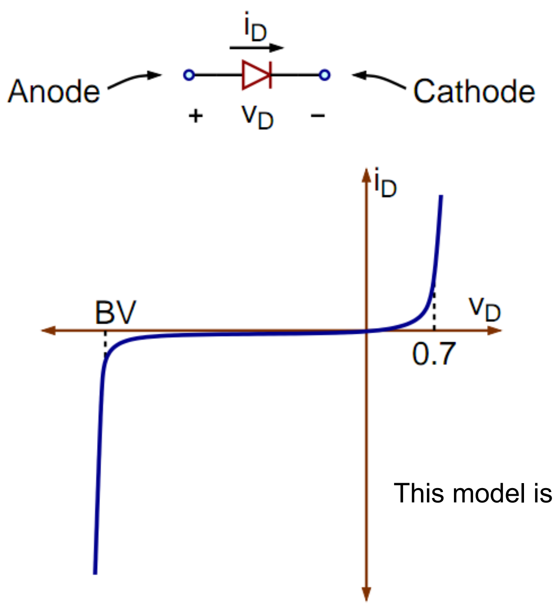
$$i_D > 0 \quad \Rightarrow \quad v_D = 0.7$$

Constant Voltage Drop Model



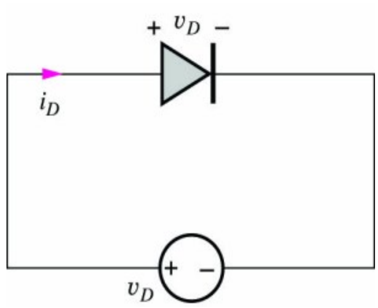
Diode drop constant voltage across it's terminal (typically *0.7V* for silicon)

Exponential *I-V* Model



This model is defined by the diode equation

Diode Equation



$$i_D = I_S\left[\exp\left(\frac{qv_D}{nkT}\right)-1\right] = I_S\left[\exp\left(\frac{v_D}{nV_T}\right)-1\right]$$

where
- I_S = reverse saturation current (A)
- v_D = voltage applied to diode (V)
- q = electronic charge (1.60 x 10^{-19} C)
- k = Boltzmann's constant (1.38 x 10^{-23} J/K)
- T = absolute temperature
- n = nonideality factor (dimensionless)
- $V_T = \frac{kT}{q}$ = thermal voltage (V) (25 mV at room temp.)

I_S is typically between 10^{-18} and 10^{-9} A, and is strongly temperature dependent due to its dependence on n_i^2. The nonideality factor is typically close to 1, but approaches 2 for devices with high current densities. It is assumed to be 1 in this text.

Diode Equation

I_S, the reverse bias saturation current for an ideal p-n diode is

$$I_S = eA\left(\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D} + \sqrt{\frac{D_n}{\tau_n}}\frac{n_i^2}{N_A}\right),$$

(Schubert 2006, 61)

where

I_S is the reverse bias saturation current,

e is elementary charge

A is the cross-sectional area

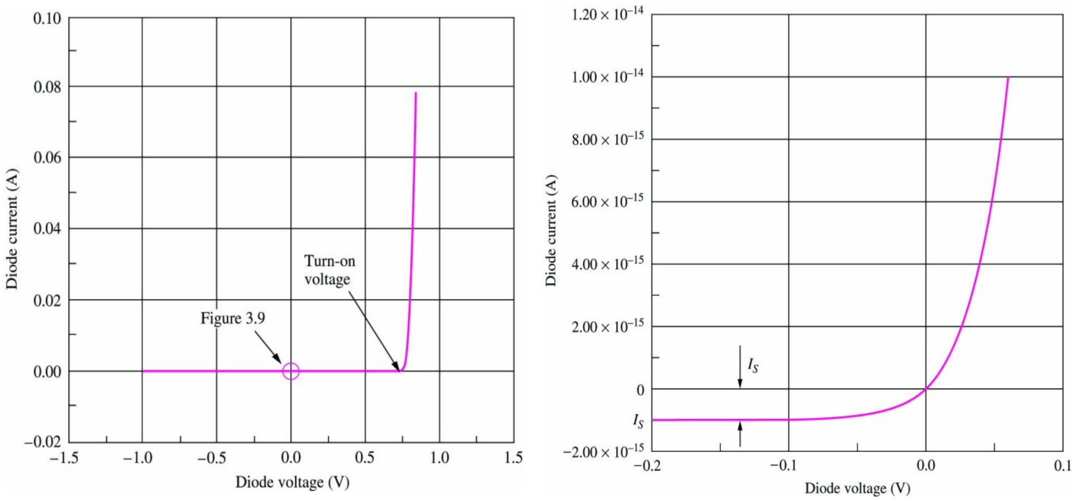
$D_{p,n}$ are the diffusion coefficients of holes and electrons, respectively,

$N_{D,A}$ are the donor and acceptor concentrations at the n side and p side, respectively,

n_i is the intrinsic carrier concentration in the semiconductor material,

$\tau_{p,n}$ are the carrier lifetimes of holes and electrons, respectively.

Diode Equation



Diode *I-V* characteristics curve showing I_s

Diode Models

- In the forward bias mode, the diode can be modeled with
  - Ideal Model
    - The diode is modeled as a switch with no resistance
  - Constant Voltage Drop Model
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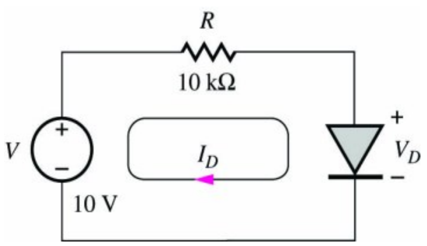
Diode Equations

- Reverse Bias: $$i_D = I_S\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right] \cong I_S[0-1] \cong -I_S$$
- No Bias: $$i_D = I_S\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right] \cong I_S[1-1] \cong 0$$
- Forward Bias: $$i_D = I_S\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right] \cong I_S \exp\left(\frac{v_D}{nV_T}\right)$$

Diode Circuit Analysis



V and R may represent the Thévenin equivalent of a more complex 2-terminal network. The objective of diode circuit analysis is to find the **quiescent operating point** for the diode.

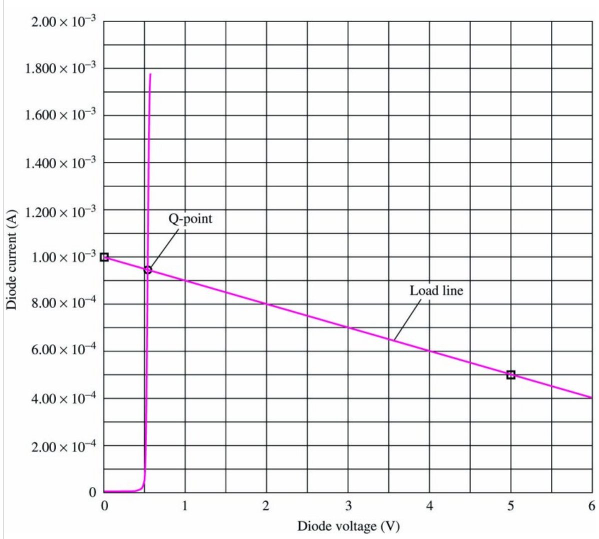
Q-Point = (I_D, V_D)

The loop equation for the diode circuit is:

$$V = I_D R + V_D$$

- This is also called the **load line** for the diode. The solution to this equation can be found by:
- Graphical analysis using the load-line method.
- Analysis with the diode's exponential model.
- Simplified analysis with the ideal diode model.
- Simplified analysis using the constant voltage drop (CVD) model.

Graphical Analysis Example



Problem: Find diode Q-point
Given data: V = 10 V, R = 10kΩ.
Analysis:

$$10 = I_D 10^4 + V_D$$

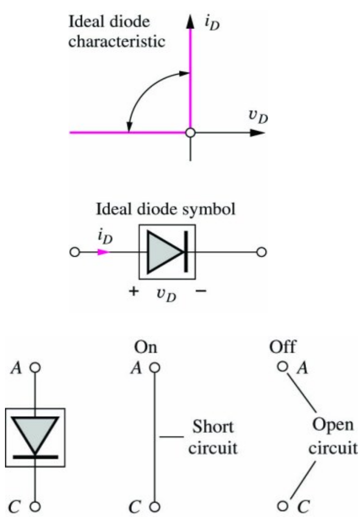
To define the load line we use,

$$\text{For } V_D = 0,\ I_D = (10V / 10k\Omega) = 1\ mA$$
$$\text{For } V_D = 5V,\ I_D = (5V / 10k\Omega) = 0.5\ mA$$

- These points and the resulting load line are plotted. Q-point is given by intersection of load line and diode characteristic:

Q-point = (0.95 mA, 0.6 V)

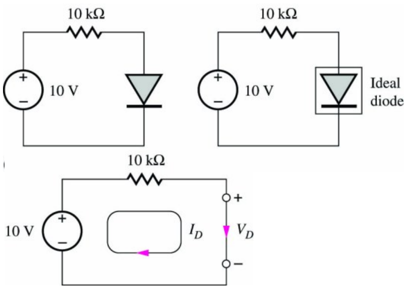
Analysis Using Ideal Model

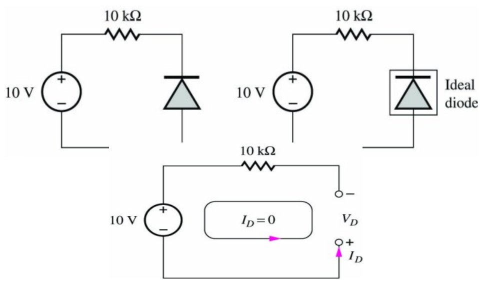


If an ideal diode is forward-biased, the voltage across the diode is zero. If an ideal diode is reverse-biased, the current through the diode is zero.
$v_D = 0$ for $i_D > 0$ and $i_D = 0$ for $v_D < 0$
Thus, the diode is assumed to be either on or off. Analysis is conducted in following steps:

- Select a diode model.
- Identify anode and cathode of the diode and label v_D and i_D.
- Guess diode's region of operation from circuit.
- Analyze circuit using diode model appropriate for assumed region of operation.
- Check results to check consistency with assumptions.

Analysis using Ideal Model





Since source appears to force positive current through diode, assume diode is on.

$$I_D = \frac{(10-0)\text{V}}{10\text{k}\Omega} = 1\text{ mA} \quad | \quad I_D \geq 0$$

Our assumption is correct, and the

Q-Point = (1 mA, 0V)

Since source is forcing current backward through diode assume diode is off. Hence $I_D = 0$. Loop equation is:

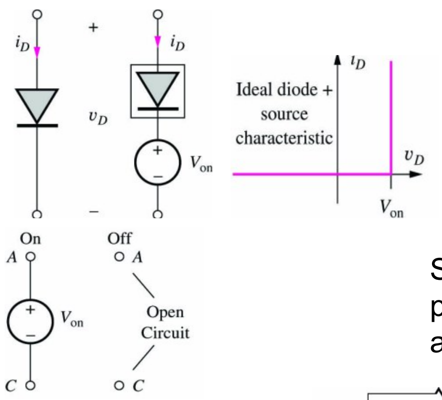
$$10 + V_D + 10^4 I_D = 0$$

$$V_D = -10V \quad | \quad V_D < 0$$

Our assumption is correct and the

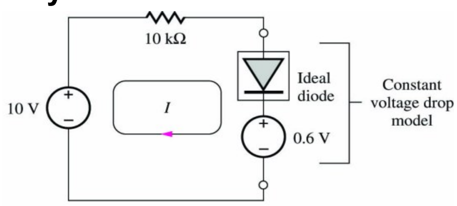
Q-Point = (0, -10 V)

Analysis using Constant Voltage Drop Model

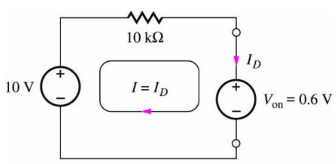


$v_D = V_{on}$ for $i_D > 0$ and $v_D = 0$ for $v_D < V_{on}$.

Analysis:



Since the 10-V source appears to force positive current through the diode, assume diode is on.

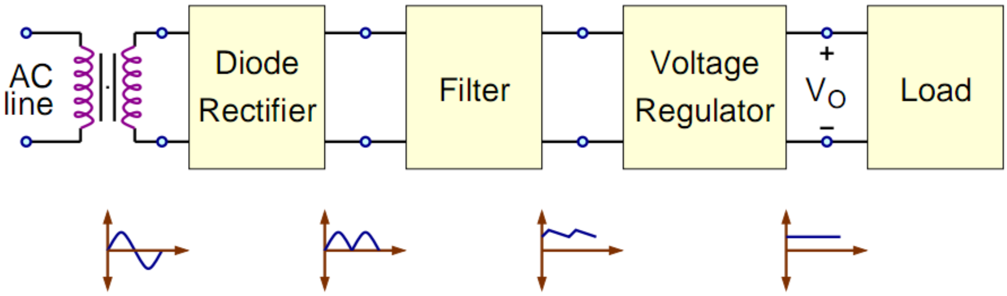


(c)

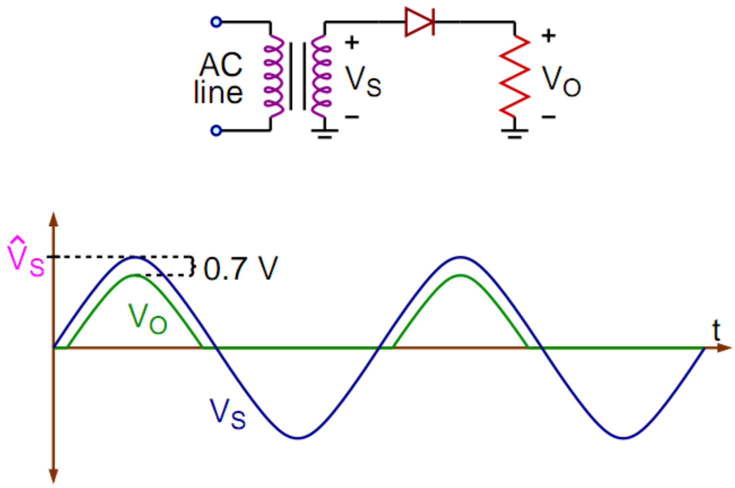
$$I_D = \frac{(10 - V_{on})\text{V}}{10\text{k}\Omega}$$

$$= \frac{(10-0.6)\text{V}}{10\text{k}\Omega} = 0.940 \text{ mA}$$

Rectifier Circuits

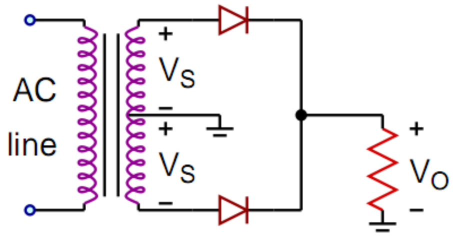


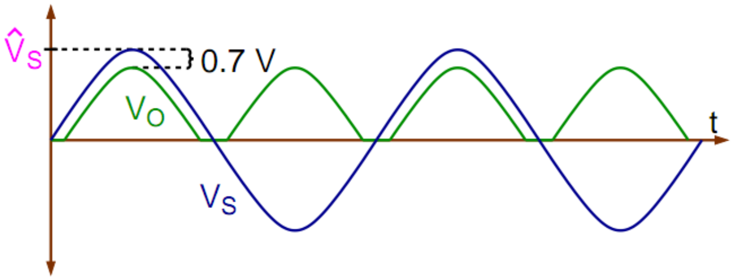
Half-Wave Rectifier



$$\mathrm{PIV} = \hat{V}_S$$

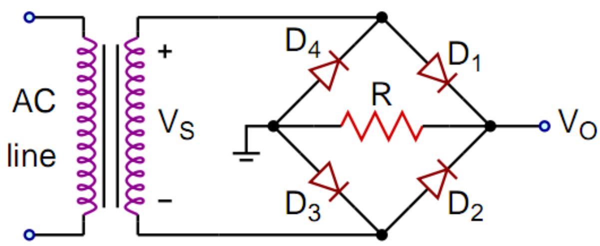
Full-Wave Rectifier

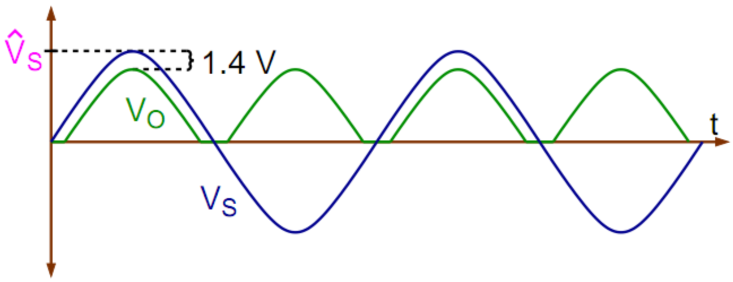




$$\mathbf{PIV} = 2\hat{V}_S - 0.7$$

Bridge Rectifier





$$\mathbf{PIV} = \hat{V}_S - 0.7$$

Next Lecture

- Diode Rectifier Circuit Analysis
- BJT