Microelectronics
Circuit Analysis and Design

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Chapter 1

Semiconductor Materials and Devices

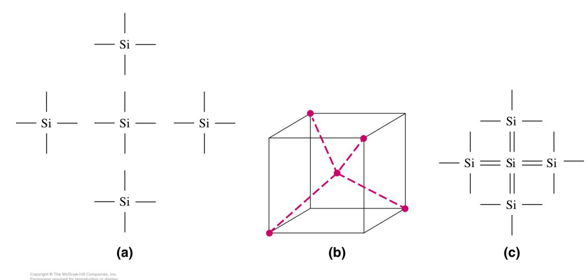
In this chapter, we will:

- Gain a basic understanding of semiconductor material properties
  - Two types of charged carriers that exist in a semiconductor
  - Two mechanisms that generate currents in a semiconductor
- Determine the properties of a pn junction
  - Ideal current–voltage characteristics of a pn junction diode
- Examine dc analysis techniques for diode circuits using various models to describe the nonlinear diode characteristics
- Develop an equivalent circuit for a diode that is used when a small, time-varying signal is applied to a diode circuit

Intrinsic Semiconductors

- Ideally 100% pure material
  - Elemental semiconductors
    - Silicon (Si)
      - Most common semiconductor used today
    - Germanium (Ge)
      - First semiconductor used in p-n diodes
  - Compound semiconductors
    - Gallium Arsenide (GaAs)

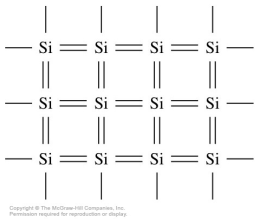
Silicon (Si)



Covalent bonding of one Si atom with **four** other Si atoms to form tetrahedral unit cell.

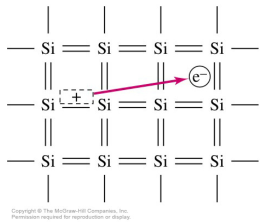
Valence electrons available at edge of crystal to bond to additional Si atoms.

Effect of Temperature



At 0°K, no bonds are broken.

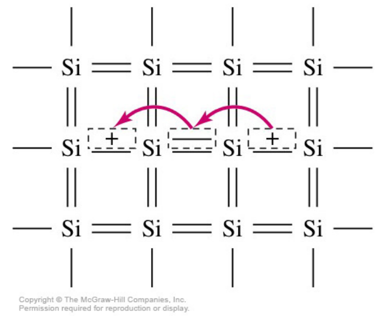
Si is an **insulator**.



As temperature increases, a bond can break, releasing a valence electron and leaving a broken bond (hole).

Current can flow.

Movement of Holes



A valence electron in a nearby bond can move to fill the broken bond, making it appear as if the 'hole' shifted locations.

Intrinsic Carrier Concentration

$$n_i = BT^{3/2} e^{\frac{-E_g}{2kT}}$$

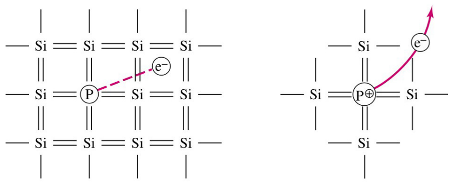
B – coefficient related to specific semiconductor
T – temperature in Kelvin
E_g – semiconductor bandgap energy
k – Boltzmann's constant

$$n_i(Si, 300K) = 1.5x10^{10}\, cm^{-3}$$

Extrinsic Semiconductors

- Impurity atoms replace some of the atoms in crystal
  - Column V atoms in Si are called donor impurities.
  - Column III in Si atoms are called acceptor impurities.

Phosphorous – Donor Impurity in Si

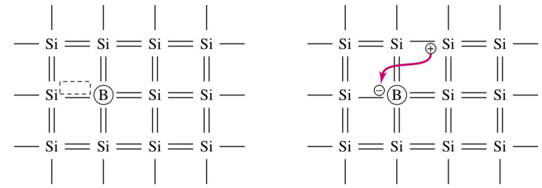


(a) (b)

Phosphorous (P) replaces a Si atom and forms four covalent bonds with other Si atoms.

The **fifth** outer shell electron of P is easily **freed** to become a conduction band electron, adding to the number of electrons available to conduct current.

Boron – Acceptor Impurity in Si



(a) (b)

Boron (B) replaces a Si atom and forms only **three** covalent bonds with other Si atoms.

The missing covalent bond is a hole, which can begin to move through the crystal when a valence electron from another Si atom is taken to form the fourth B-Si bond.

Electron and Hole Concentrations

ni = intrinsic carrier concentration (geo. Mean)
n = electron concentration
p = hole concentration

$$n_i^2 = n \cdot p$$

n-type:

n = N_D, the donor concentration

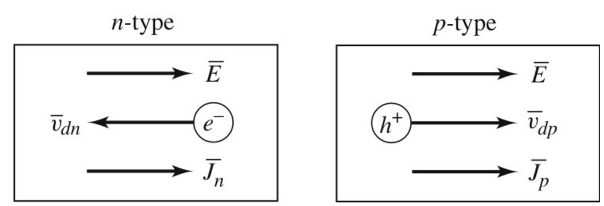
$$p = n_i^2 / N_D$$

p-type:

p = N_A, the acceptor concentration

$$n = n_i^2 / N_A$$

Drift Currents

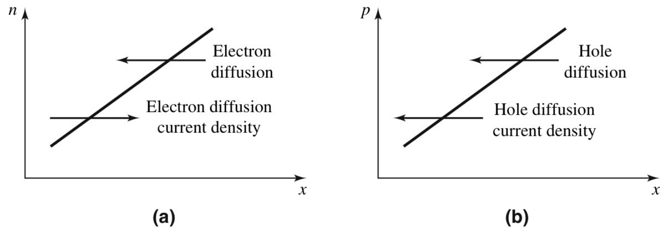


(a) (b)

Electrons and hole flow in opposite directions when under the influence of an electric field at different velocities.

The drift currents associated with the electrons and holes are in the same direction.

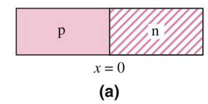
Diffusion Currents



Both electrons and holes flow from high concentration to low.

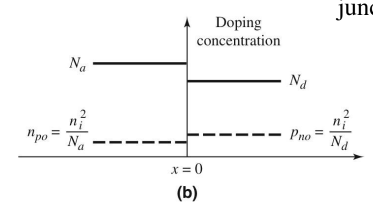
The diffusion current associated with the electrons flows in the opposite direction when compared to that of the holes.

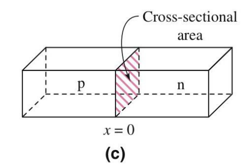
p-n Junctions



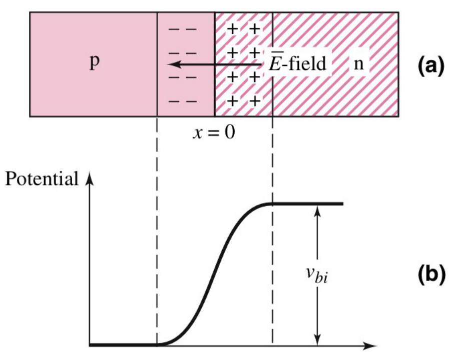
A simplified 1-D sketch of a p-n junction (a) has a doping profile (b).

The 3-D representation (c) shows the cross sectional area of the junction.





Built-in Potential



This movement of carriers creates a space charge or depletion region with an induced electric field near x = 0.

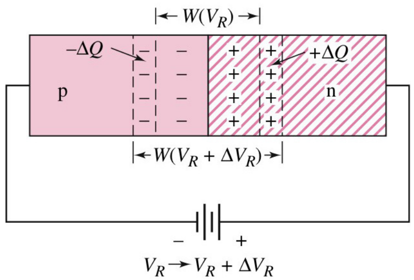
A potential voltage, v_{bi}, is developed across the junction.

Built-in Potential

$$V_{bi} = \frac{kT}{e}\ln\left[\frac{N_a N_d}{n_i^2}\right] = V_T \ln\left[\frac{N_a N_d}{n_i^2}\right]$$

- $V_T = \frac{kT}{e} = thermal\ voltage = 0.026$ V
- k = Boltzman's constant
- T = absolute temperature
- e = electric charge magnitude
- N_a = acceptor concentration
- N_d = donor concentration
- n_i = intrinsic carrier concentration

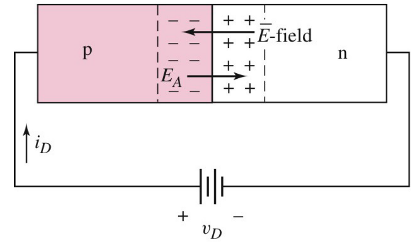
Reverse Bias



Increase in space-charge width, W, as V_R increases to $V_R+\Delta V_R$.

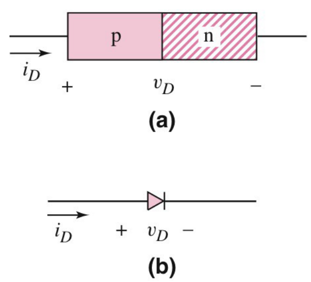
Creation of more fixed charges ($-\Delta Q$ and $+\Delta Q$) leads to junction capacitance.

Forward Biased p-n Junction



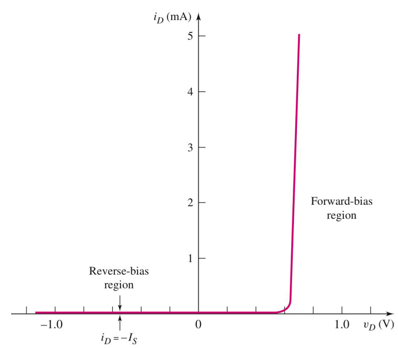
Applied voltage, v_D, induces an electric field, E_A, in the opposite direction as the original space-charge electric field, resulting in a smaller net electric field and smaller barrier between n and p regions.

Circuit Symbol



Conventional current direction and polarity of voltage drop is shown

Ideal Current-Voltage (I-V) Characteristics



The p-n junction only conducts significant current in the forward-bias region.

i_D is an exponential function in this region.

Essentially no current flows in reverse bias.

Ideal Diode Equation

A fit to the I-V characteristics of a diode yields the following equation, known as the ideal diode equation:

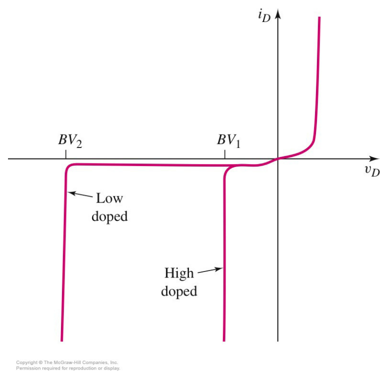
$$I_D = I_s\left(e^{\frac{qv_D}{kT}} - 1\right)$$

kT/q is also known as the thermal voltage, V_T.

V_T = 25.9 mV when T = 300K, room temperature.

$$\boxed{I_D = I_s\left(e^{\frac{v_D}{V_T}} - 1\right)}$$

Breakdown Voltage

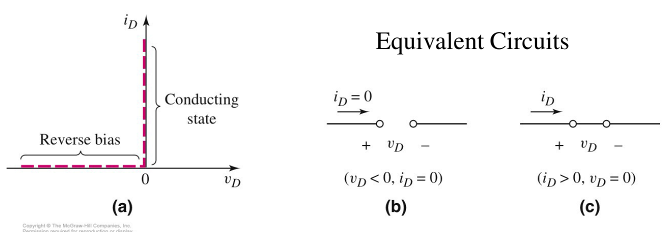


The magnitude of the breakdown voltage (BV) is smaller for heavily doped diodes as compared to more lightly doped diodes.

Current through a diode increases rapidly once breakdown has occurred.

dc Model of Ideal Diode

Equivalent Circuits

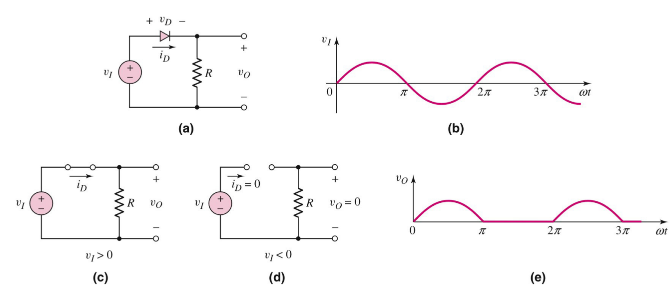


Assumes $v_{bi} = 0$.

No current flows when reverse biased (b).

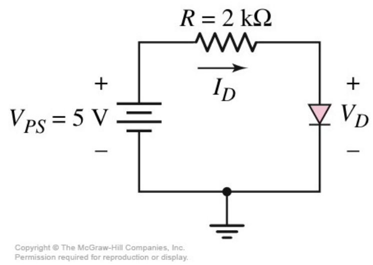
No internal resistance to limit current when forward biased (c).

Half-Wave Diode Rectifier



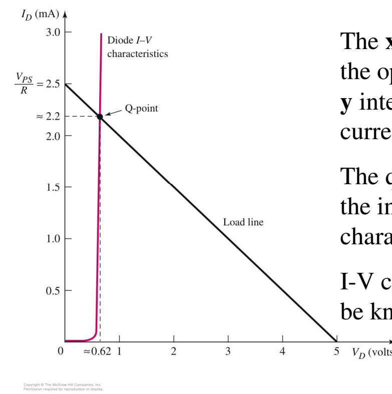
Diode only allows current to flow through the resistor when $v_I \geq 0$V. Forward-bias equivalent circuit is used to determine v_O under this condition.

Graphical Analysis Technique



Simple diode circuit where I_D and V_D are not known.

Load Line Analysis

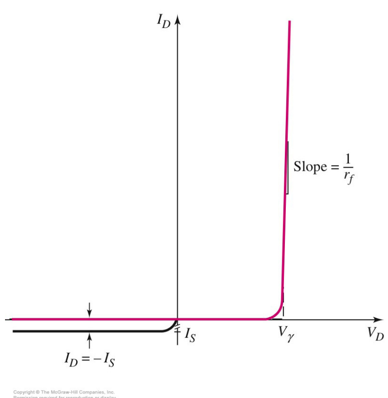


The **x** intercept of the load line is the open circuit voltage and the **y** intercept is the short circuit current.

The quiescent point or Q-point is the intersection of diode I-V characteristic with the load line.

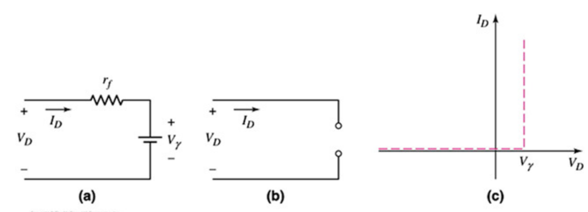
I-V characteristics of diode must be known.

Piecewise Linear Model



Two linear approximations are used to form piecewise linear model of diode.

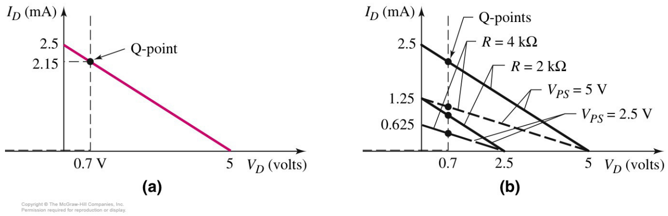
Diode Piecewise Equivalent Circuit



The diode is replaced by a battery with voltage, V_γ, with a a resistor, r_f, in series when in the 'on' condition (a) and is replaced by an open when in the 'off' condition, $V_D < V_\gamma$.

If $r_f = 0$, $V_D = V_\gamma$ when the diode is conducting.

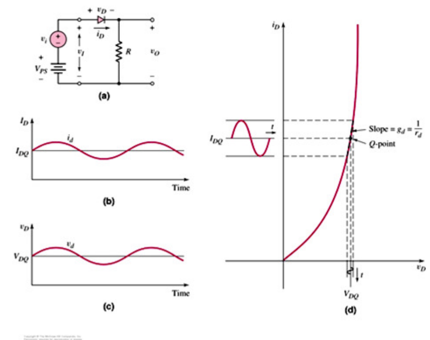
Q-point



The **x** intercept of the load line is the open circuit voltage and the **y** intercept is the short circuit current.

The Q-point is dependent on the power supply voltage and the resistance of the rest of the circuit as well as on the diode I-V characteristics.

ac Circuit Analysis



Combination of dc and sinusoidal input voltages modulate the operation of the diode about the Q-point.

ac Circuit Analysis

$$v_D = V_D + v_d$$

$$i_D = I_s\left(e^{\frac{v_D}{V_T}} - 1\right) \cong I_s\left(e^{\frac{v_D}{V_T}}\right) = I_s\left(e^{\frac{V_D}{V_T}}\right)\ \left(e^{\frac{v_d}{V_T}}\right)$$

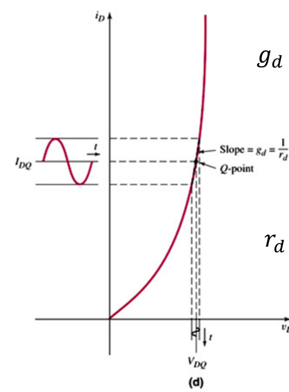
For small signals when $v_d \ll V_T$

$$e^{v_d/V_T} \cong 1 + {}^{v_d}/_{V_T}$$

Then $I_s\left(e^{\frac{V_D}{V_T}}\right)\left(1 + {}^{v_d}/_{V_T}\right) = I_D\left(1 + {}^{v_d}/_{V_T}\right) = I_{DQ} + i_d$

$$I_{DQ} \equiv I_s\left(e^{\frac{V_D}{V_T}}\right) \quad \text{and} \quad i_d \equiv \left(\frac{I_{DQ}}{V_T}\right) v_d$$

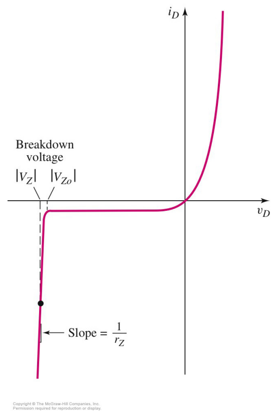
ac Circuit Analysis

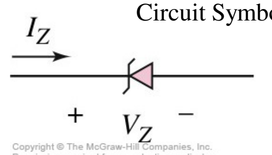


$$g_d \equiv \left(\frac{I_{DQ}}{V_T}\right) = small\ signal\ conductance$$

$$r_d \equiv \left(\frac{V_T}{I_{DQ}}\right) = small\ signal\ resistance$$

Zener Diode I-V Characteristics



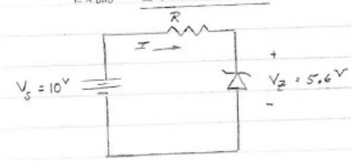


Circuit Symbol

Usually operated in reverse bias region near the breakdown or Zener voltage, V_Z.

Note the convention for current and polarity of voltage drop.

Ex. Zener Diode



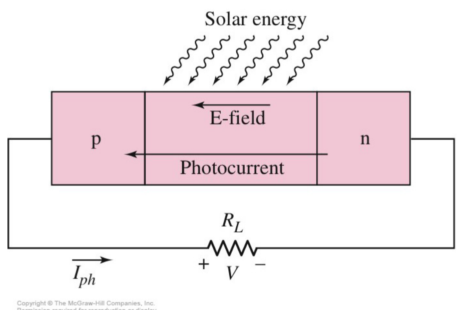
assume $r_Z = 0$

Find R to limit $I < 3^{mA}$

$I = \frac{V_S - V_Z}{R} \Rightarrow R = \frac{10 - 5.6}{3^{mA}} = \underline{1.47 k\Omega}$

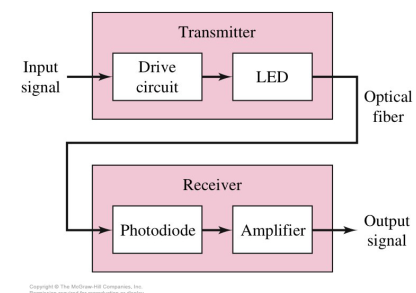
The output voltage will remain at 5.6^V even if the current or power supply voltage change over time.

Photogenerated Current



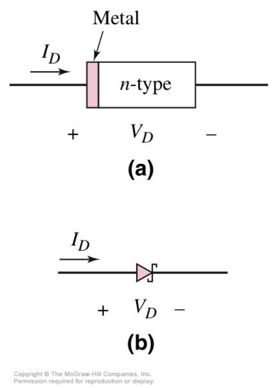
When the energy of the photons is greater than E_g, the photon's energy can be used to break covalent bonds and generate an equal number of electrons and holes to the number of photons absorbed.

Optical Transmission System



LED (**L**ight **E**mitting **Diode**) and photodiode are p-n junctions.

Schottky Barrier Diode

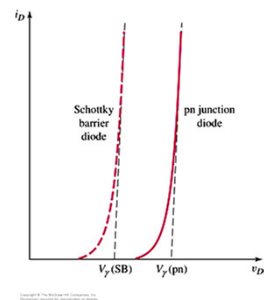


A metal layer replaces the p region of the diode.

Circuit symbol showing conventional current direction of current and polarity of voltage drop.

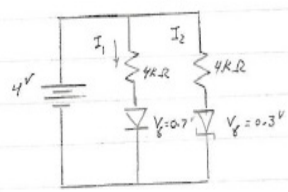
Comparison of I-V Characteristics:

Forward Bias



The built-in voltage of the Schottky barrier diode, V_γ(SB), is about ½ as large as the built-in voltage of the p-n junction diode, V_γ(pn),.

Ex. Schottky Diode



* let $r_f = 0$.

$$I_1 = \frac{4-0.7}{4} = 0.825 \text{ mA}$$

$$I_2 = \frac{4-0.3}{4} = 0.925 \text{ mA}$$