ELECTRONIC DEVICES AND CIRCUIT THEORY

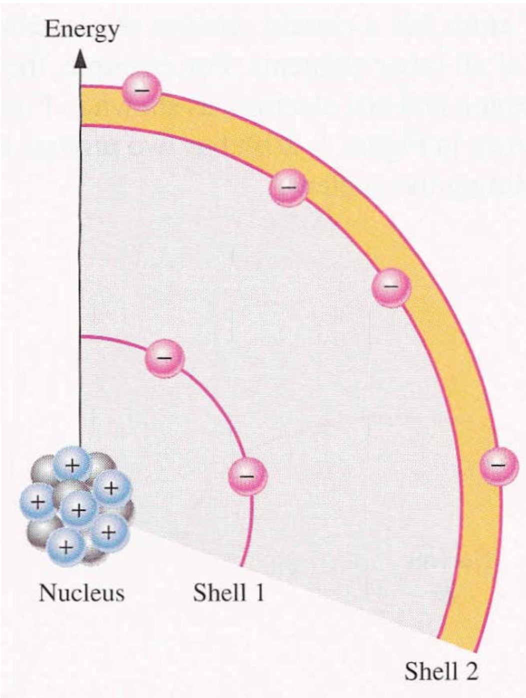
TENTH EDITION

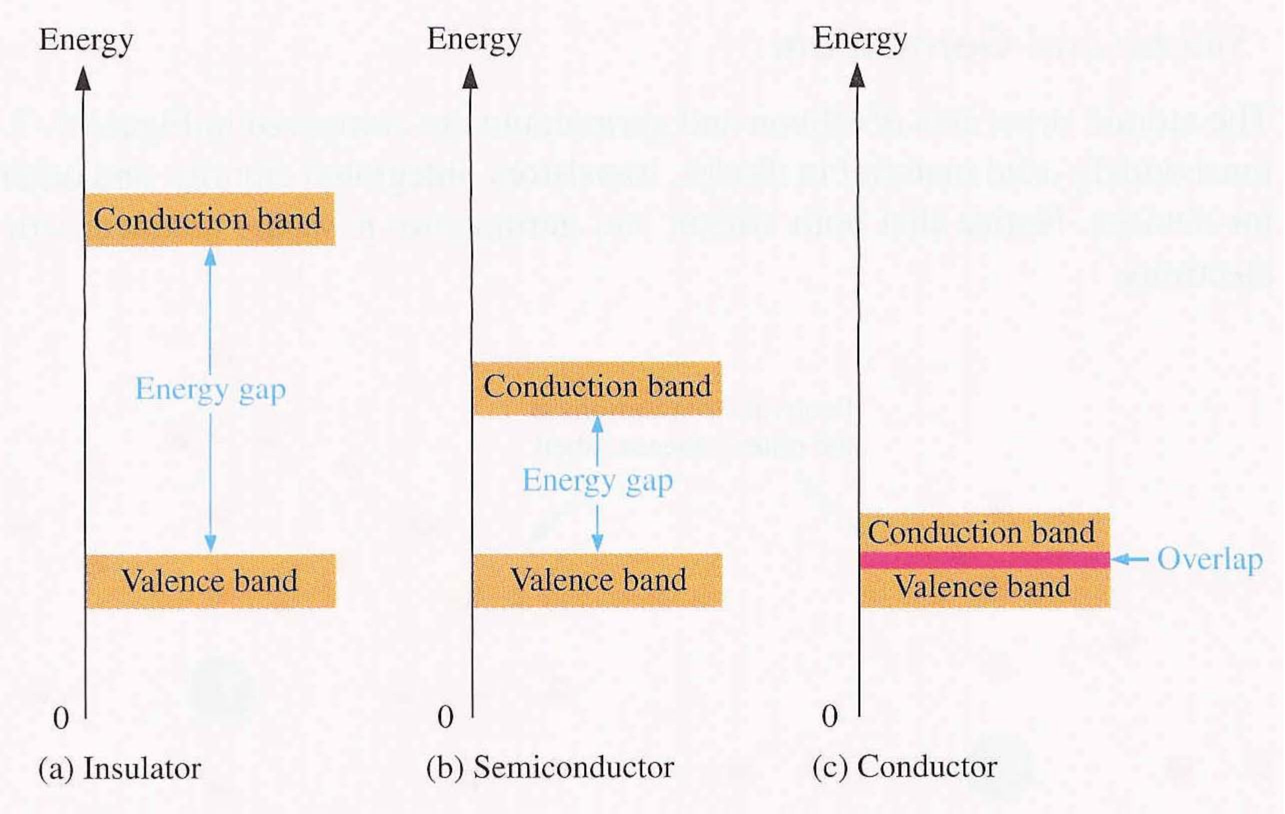
BOYLESTAD

PEARSON

Chapter 1:
Semiconductor Diodes

Semiconductors, Insulators, Conductors

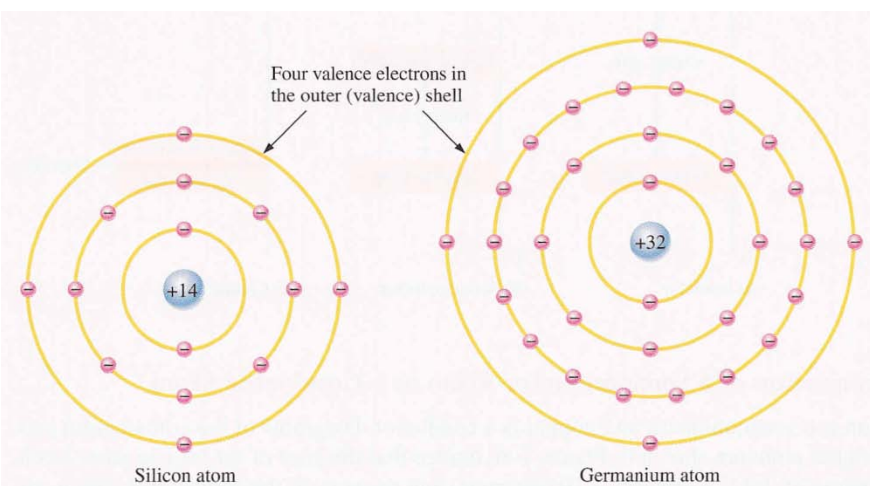


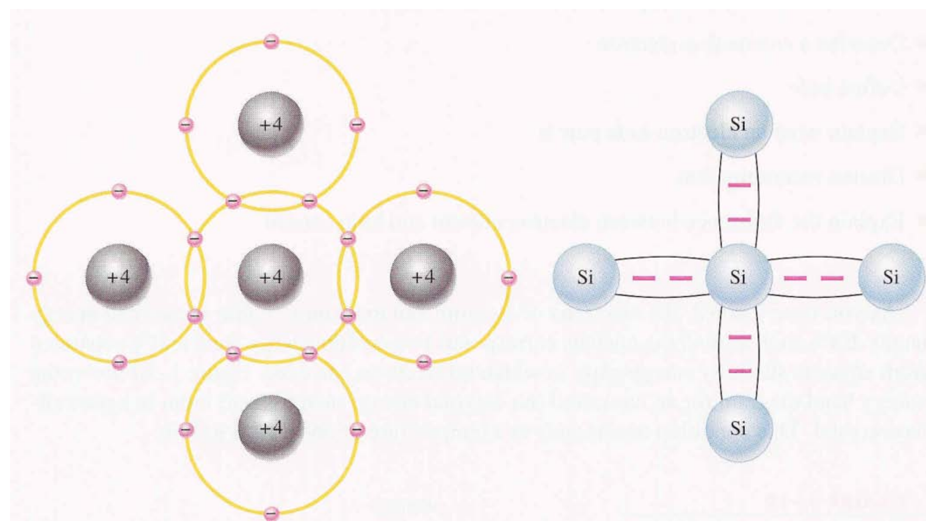


Semiconductor Materials

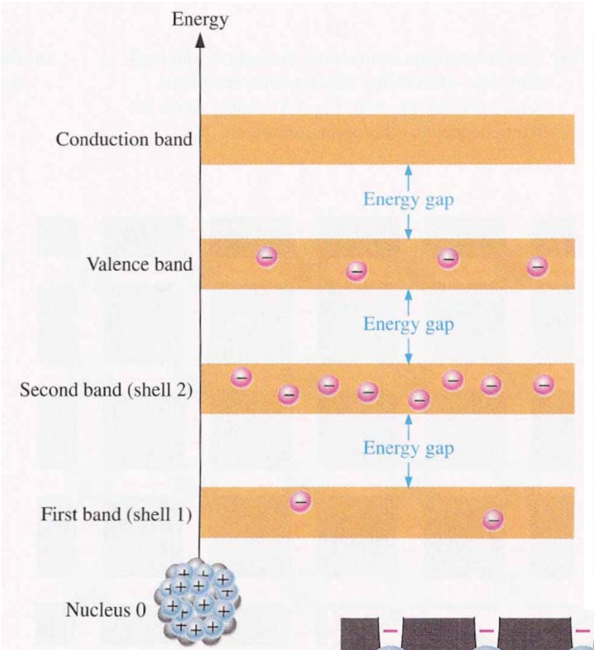
Materials commonly used in the development of semiconductor devices:

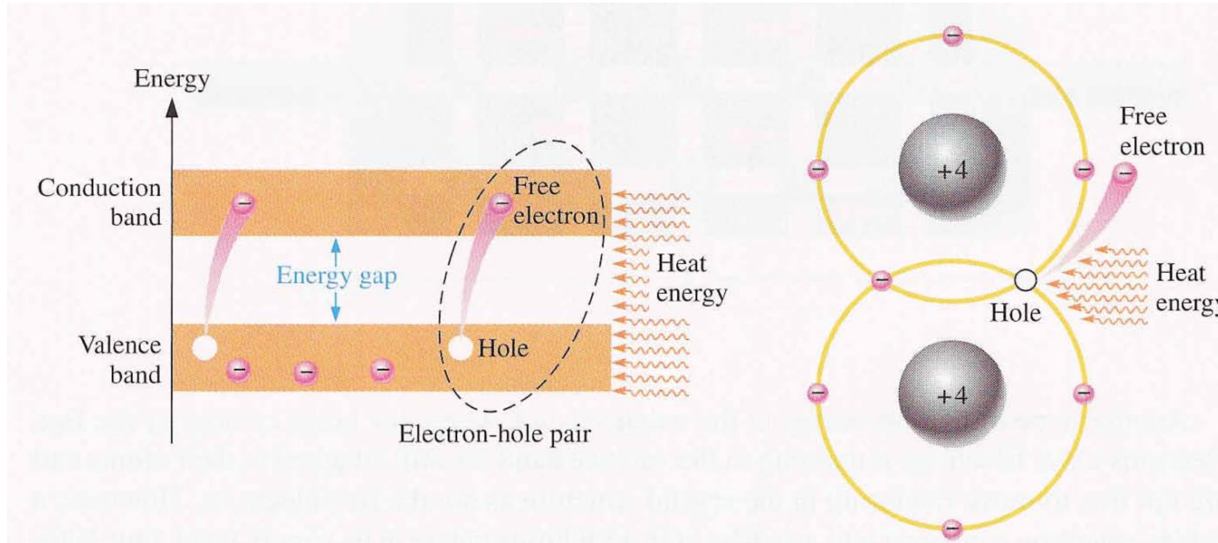
- **Silicon (Si)**
- **Germanium (Ge)**
- **Gallium Arsenide (GaAs)**

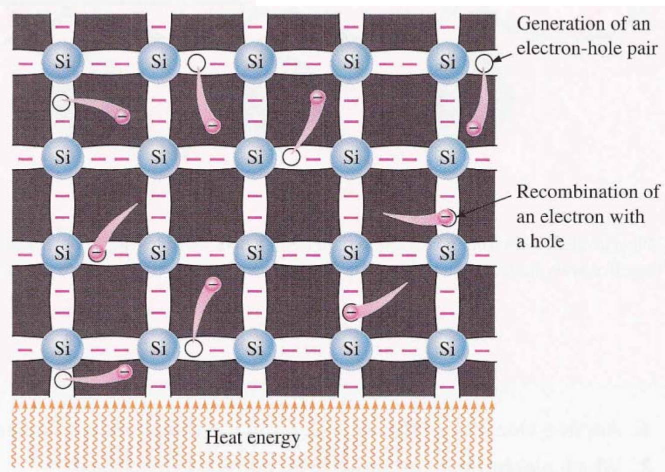


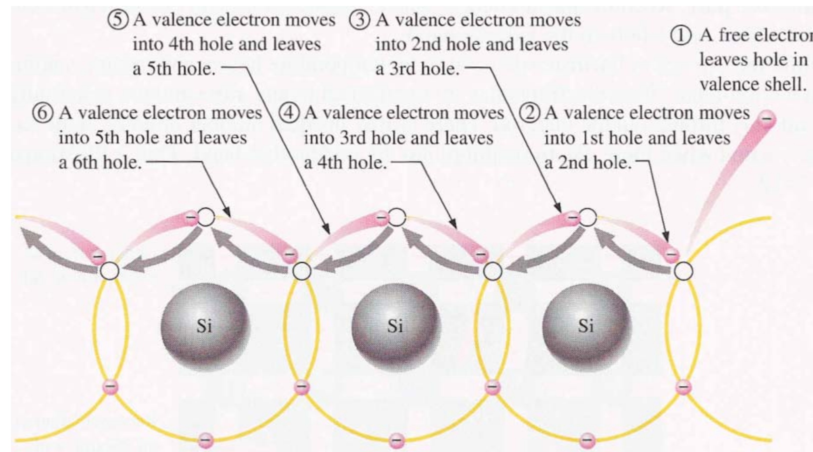


Conduction in Semiconductors





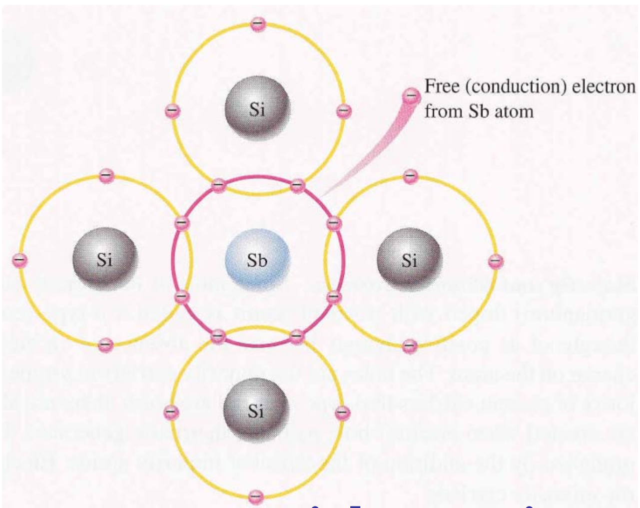




Doping

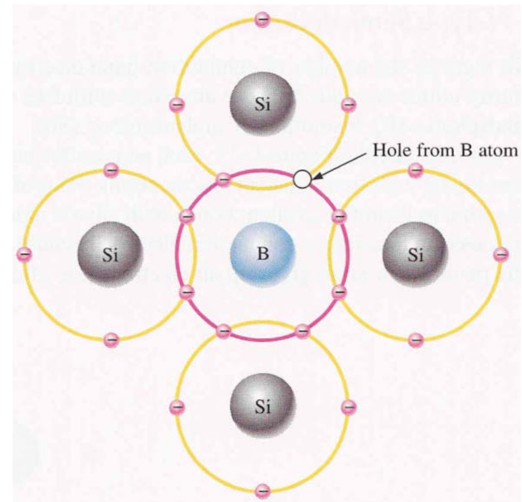
The electrical characteristics of silicon and germanium are improved by adding materials in a process called doping.

There are just two types of doped semiconductor materials:



***n*-type**

***p*-type**



- ***n*-type materials contain an excess of conduction band electrons.**
- ***p*-type materials contain an excess of valence band holes.**

Majority and Minority Carriers

Two currents through a diode:

Majority Carriers

- **The majority carriers in *n*-type materials are electrons.**
- **The majority carriers in *p*-type materials are holes.**

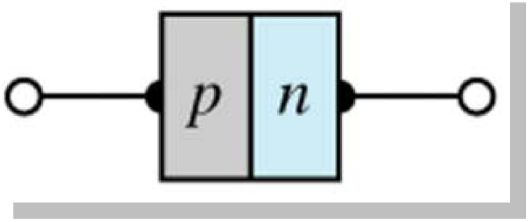
Minority Carriers

- **The minority carriers in *n*-type materials are holes.**
- **The minority carriers in *p*-type materials are electrons.**

p-n Junctions

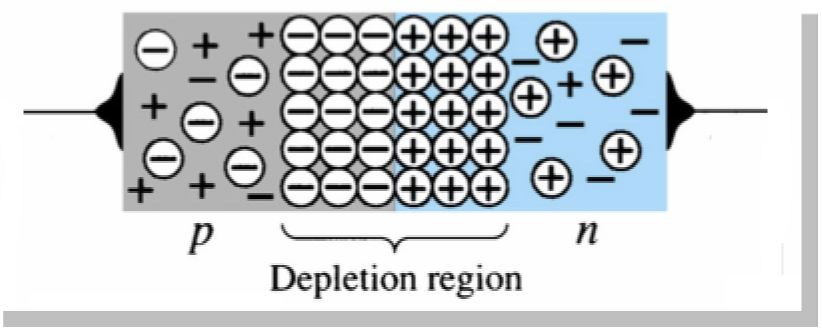
One end of a silicon or germanium crystal can be doped as a *p*-type material and the other end as an *n*-type material.

The result is a ***p-n* junction**.



p-n Junctions

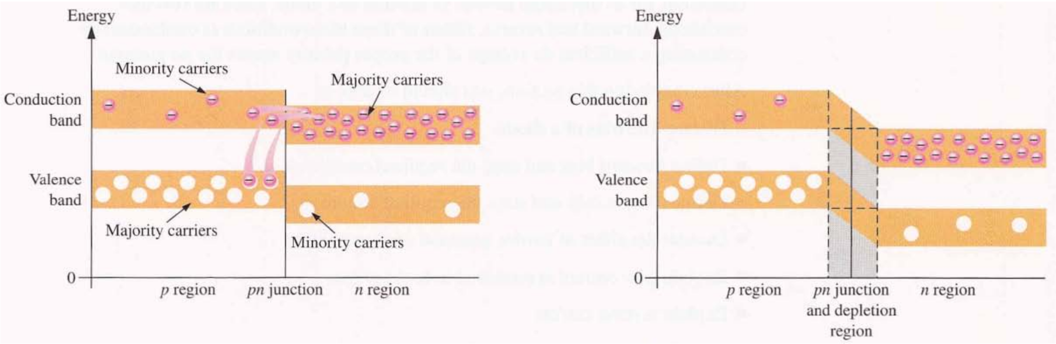
At the *p-n* junction, the excess conduction-band electrons on the *n*-type side are attracted to the valence-band holes on the *p*-type side.



The electrons in the *n*-type material migrate across the junction to the *p*-type material (electron flow).

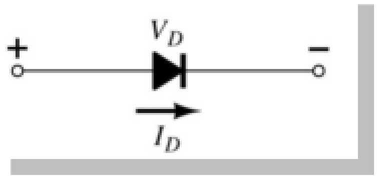
The result is the formation of a depletion region around the junction.

The electron migration results in a negative charge on the p-type side of the junction and a positive charge on the n-type side of the junction.

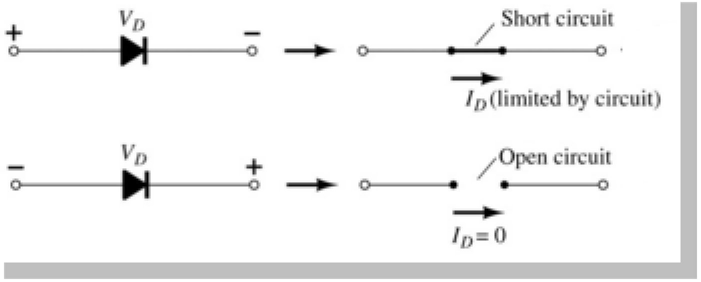


Diodes

The diode is a 2-terminal device.



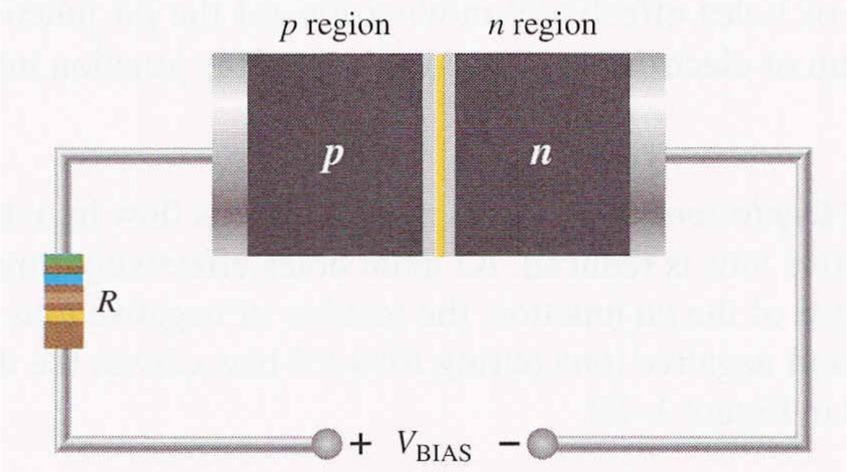
A diode ideally conducts in only one direction.



Diode Operating Conditions

A diode has three operating conditions:

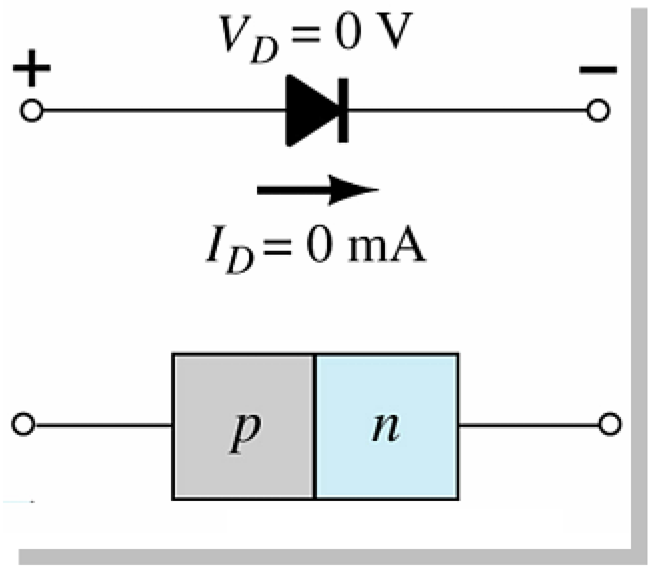
- **No bias**
- **Forward bias**
- **Reverse bias**



Diode Operating Conditions

No Bias

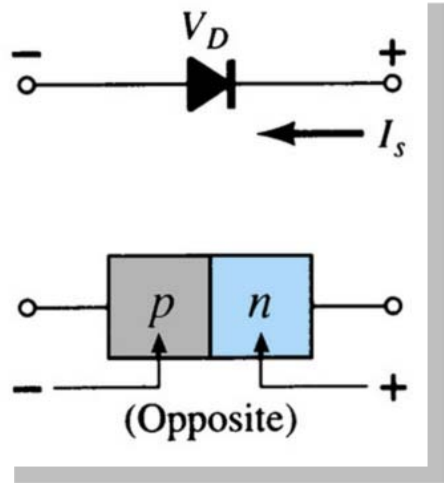
- No external voltage is applied: $V_D = 0$ V
- No current is flowing: $I_D = 0$ A
- Only a modest depletion region exists

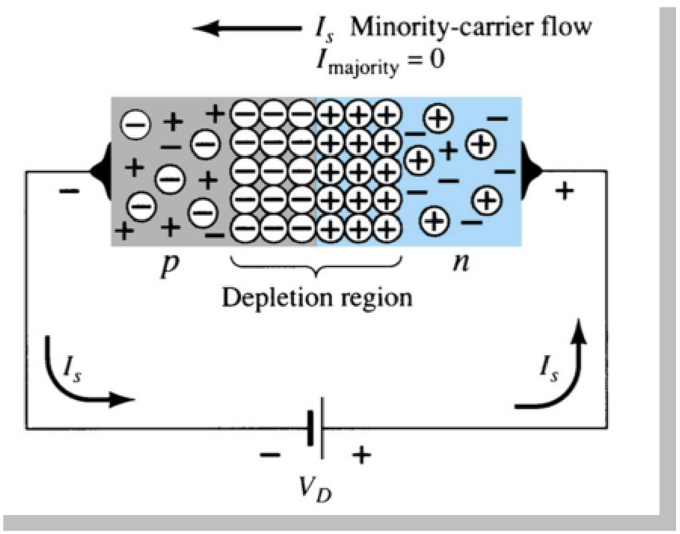


Diode Operating Conditions

Reverse Bias

External voltage is applied across the *p-n* junction in the opposite polarity of the *p-* and *n-*type materials.



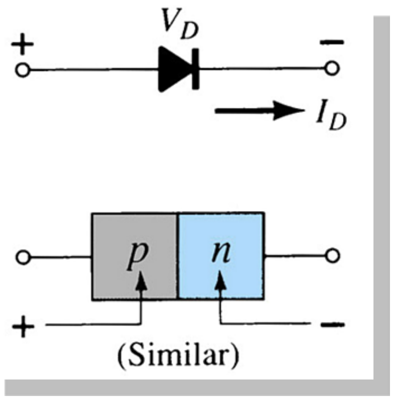


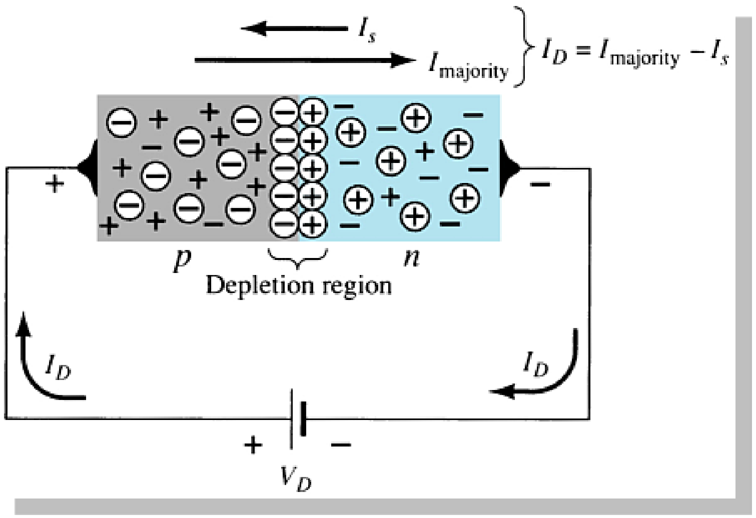
- **The reverse voltage causes the depletion region to widen.**
- **The electrons in the *n*-type material are attracted toward the positive terminal of the voltage source.**
- **The holes in the *p*-type material are attracted toward the negative terminal of the voltage source.**

Diode Operating Conditions

Forward Bias

External voltage is applied across the *p-n* junction in the same polarity as the *p-* and *n*-type materials.

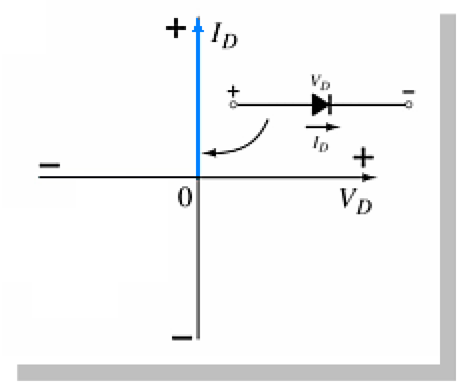




- The forward voltage causes the depletion region to narrow.
- The electrons and holes are pushed toward the *p-n* junction.
- The electrons and holes have sufficient energy to cross the *p-n* junction.

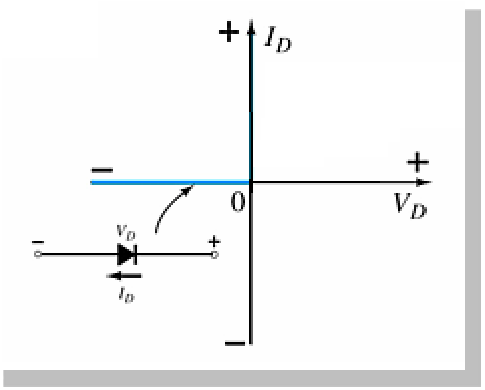
Diode Characteristics

Conduction Region



- The voltage across the diode is 0 V
- The current is infinite
- The forward resistance is defined as
  $R_F = V_F / I_F$
- The diode acts like a short

Non-Conduction Region



- All of the voltage is across the diode
- The current is 0 A
- The reverse resistance is defined as
  $R_R = V_R / I_R$
- The diode acts like open

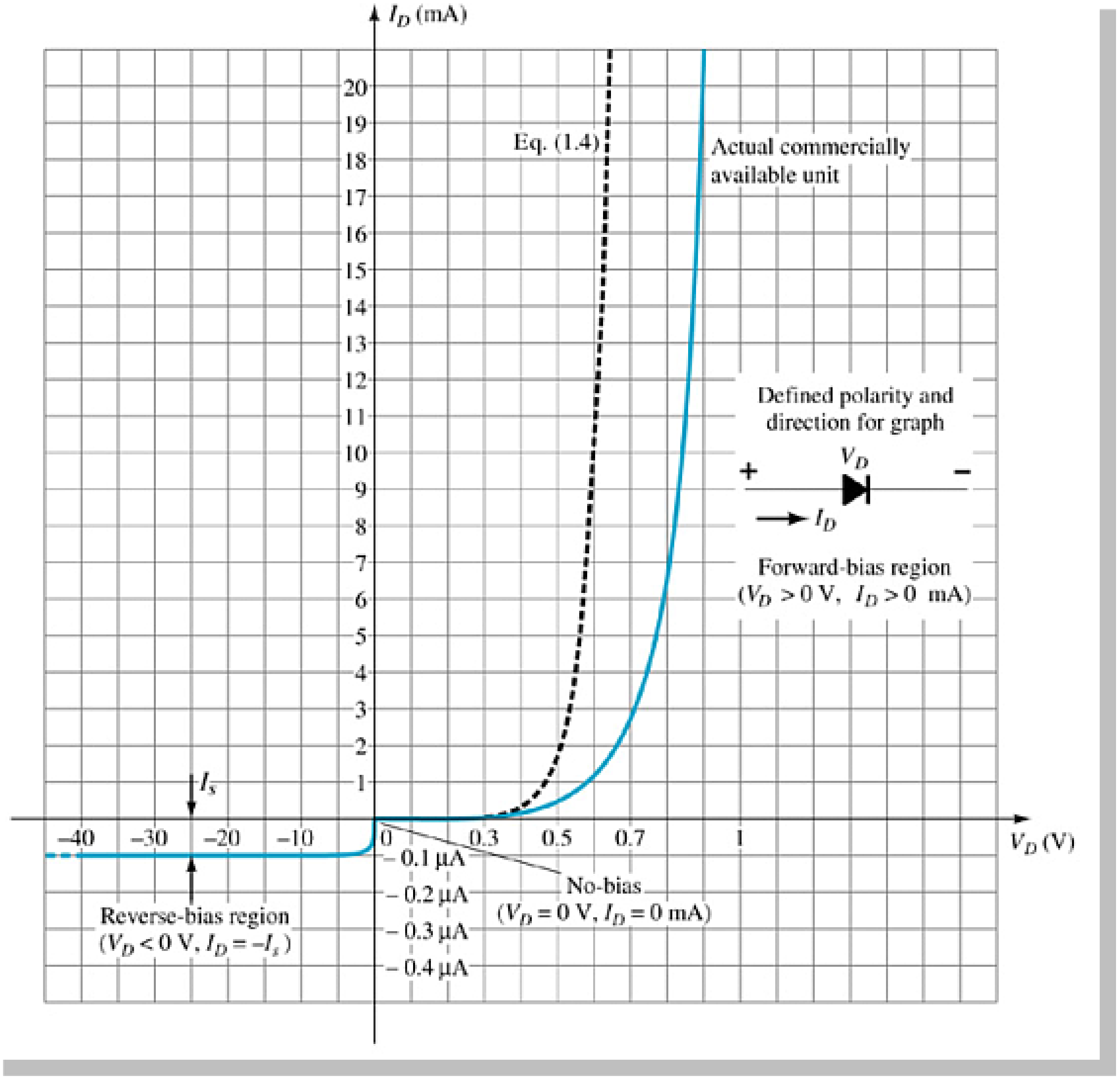
Actual Diode Characteristics

Note the regions for no bias, reverse bias, and forward bias conditions.

Carefully note the scale for each of these conditions.

$$I_D = I_S\left(e^{V_D/nV_T} - 1\right)$$

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

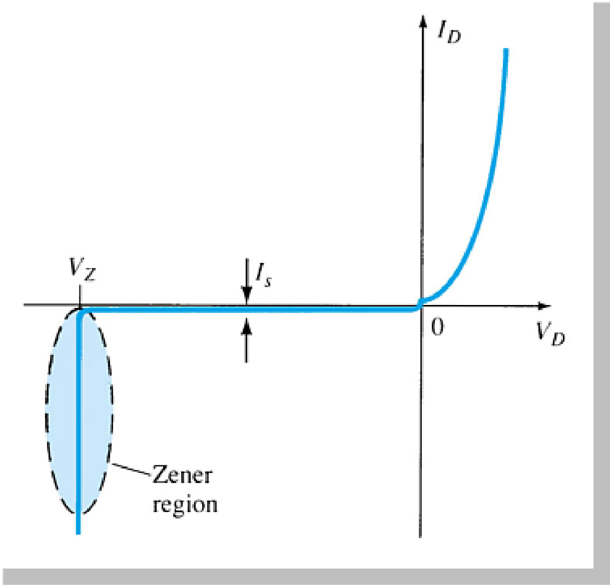


Zener Region

The Zener region is in the diode's reverse-bias region.

At some point the reverse bias voltage is so large the diode breaks down and the reverse current increases dramatically.

- **The maximum reverse voltage that won't take a diode into the zener region is called the peak inverse voltage or peak reverse voltage.**
- **The voltage that causes a diode to enter the zener region of operation is called the zener voltage (V_Z).**



Forward Bias Voltage

The point at which the diode changes from no-bias condition to forward-bias condition occurs when the electrons and holes are given sufficient energy to cross the *p-n* junction. This energy comes from the external voltage applied across the diode.

The forward bias voltage required for a:

- **gallium arsenide diode ≅ 1.2 V**
- **silicon diode ≅ 0.7 V**
- **germanium diode ≅ 0.3 V**

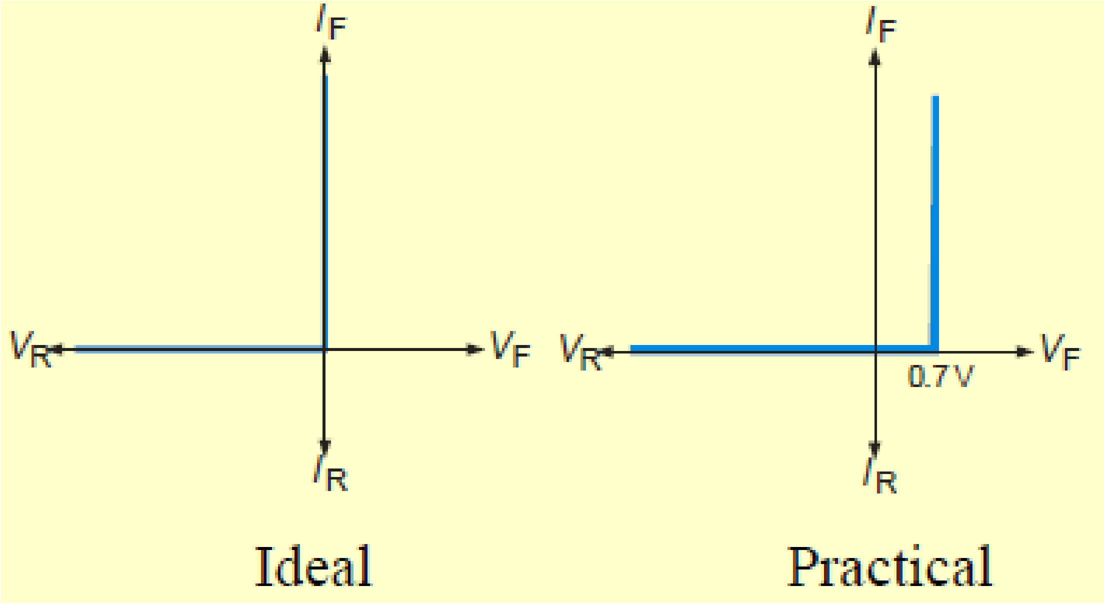
Temperature Effects

As temperature increases it adds energy to the diode.

- It reduces the required forward bias voltage for forward-bias conduction.
- It increases the amount of reverse current in the reverse-bias condition.
- It increases maximum reverse bias avalanche voltage.

Germanium diodes are more sensitive to temperature variations than silicon or gallium arsenide diodes.

IDEAL VERSUS PRATICAL



Resistance Levels

Semiconductors react differently to DC and AC currents.

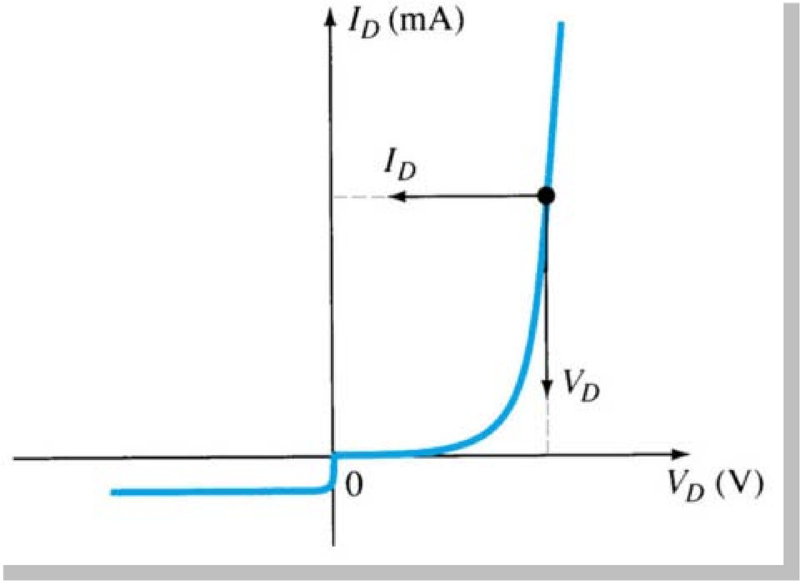
There are three types of resistance:

- **DC (static) resistance**
- **AC (dynamic) resistance**
- **Average AC 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

In the forward bias region:

$$r'_d = \frac{26\,\text{mV}}{I_D} + r_B$$

- **The resistance depends on the amount of current (I_D) in the diode.**
- **The voltage across the diode is fairly constant (26 mV for 25°C).**
- **r_B ranges from a typical 0.1 Ω for high power devices to 2 Ω for low power, general purpose diodes. In some cases r_B can be ignored.**

In the reverse bias region:

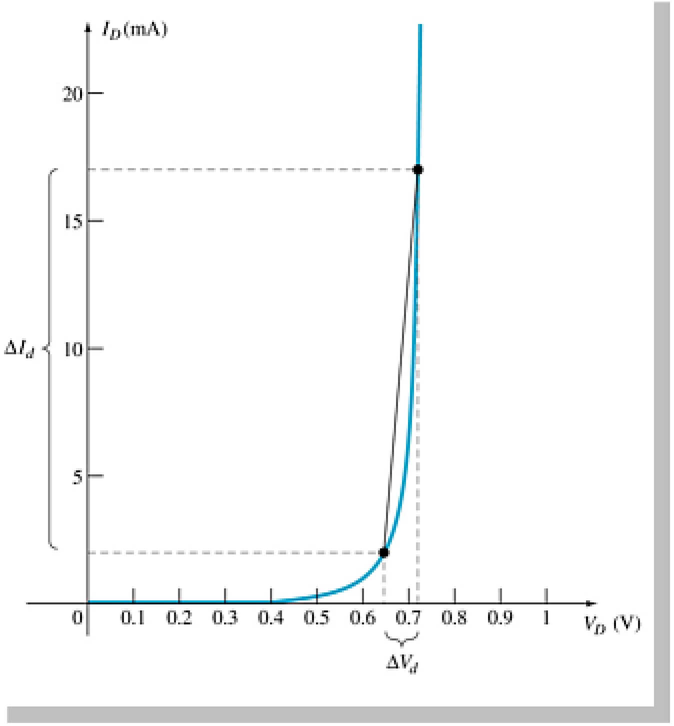
$$r'_d = \infty$$

The resistance is effectively infinite. The diode acts like an open.

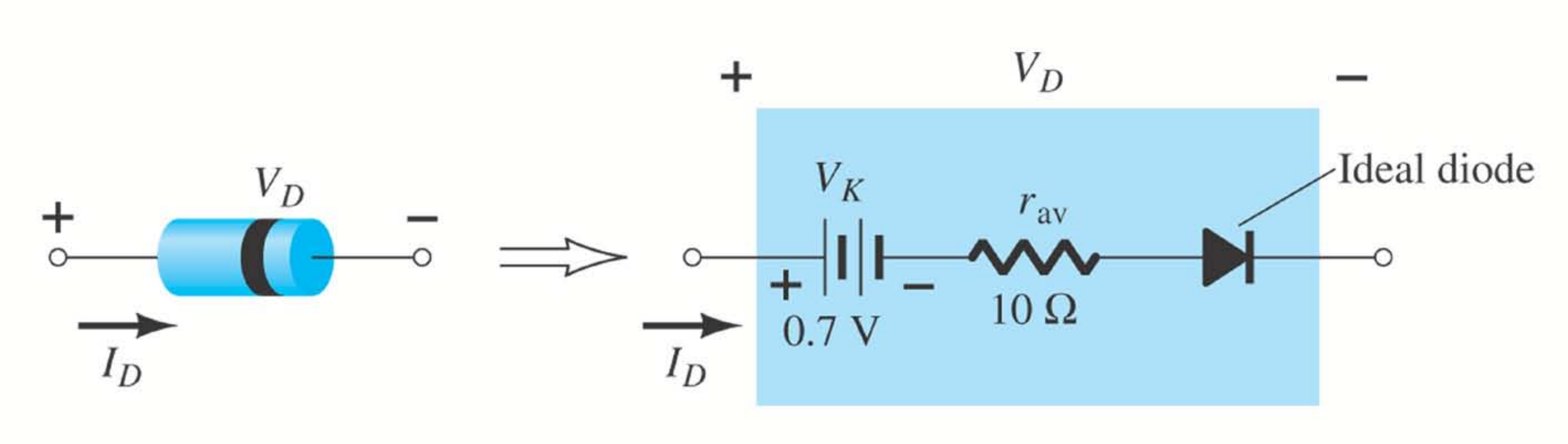
Average AC Resistance

$$r_{av} = \frac{\Delta V_d}{\Delta I_d} \bigg| \text{pt. to pt.}$$

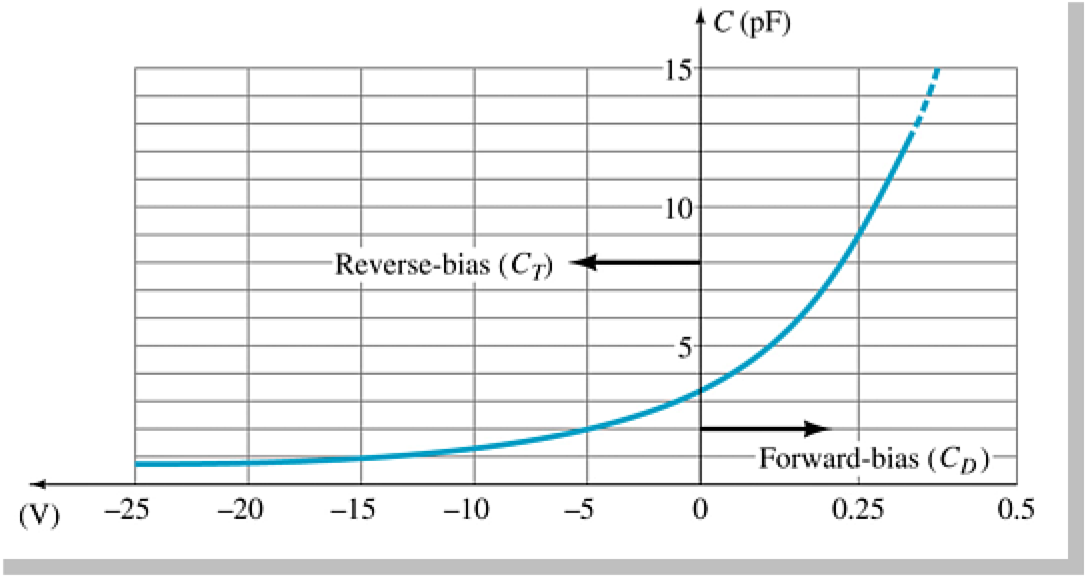
AC resistance can be calculated using the current and voltage values for two points on the diode characteristic curve.



Diode Equivalent Circuit



Diode Capacitance

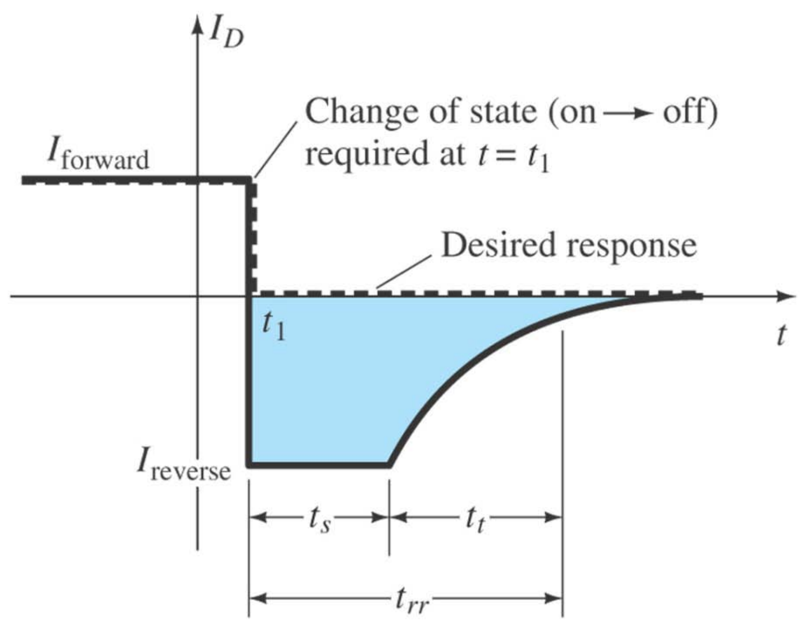


In reverse bias, the depletion layer is very large. The diode's strong positive and negative polarities create capacitance, C_T. The amount of capacitance depends on the reverse voltage applied.

In forward bias storage capacitance or diffusion capacitance (C_D) exists as the diode voltage increases.

Reverse Recovery Time (t_{rr})

Reverse recovery time is the time required for a diode to stop conducting once it is switched from forward bias to reverse bias.

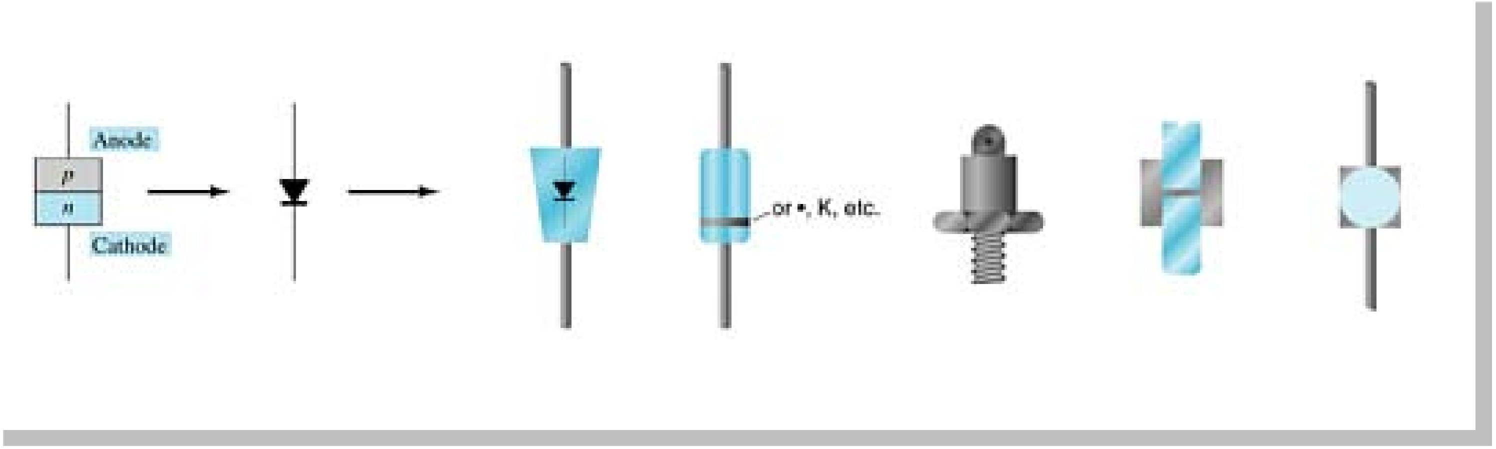


Diode Specification Sheets

Data about a diode is presented uniformly for many different diodes. This makes cross-matching of diodes for replacement or design easier.

1. **Forward Voltage (V_F) at a specified current and temperature**
2. **Maximum forward current (I_F) at a specified temperature**
3. **Reverse saturation current (I_R) at a specified voltage and temperature**
4. **Reverse voltage rating, PIV or PRV or V(BR), at a specified temperature**
5. **Maximum power dissipation at a specified temperature**
6. **Capacitance levels**
7. **Reverse recovery time, t_{rr}**
8. **Operating temperature range**

Diode Symbol and Packaging



The anode is abbreviated A
The cathode is abbreviated K

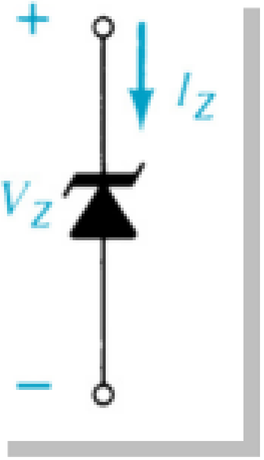
Other Types of Diodes

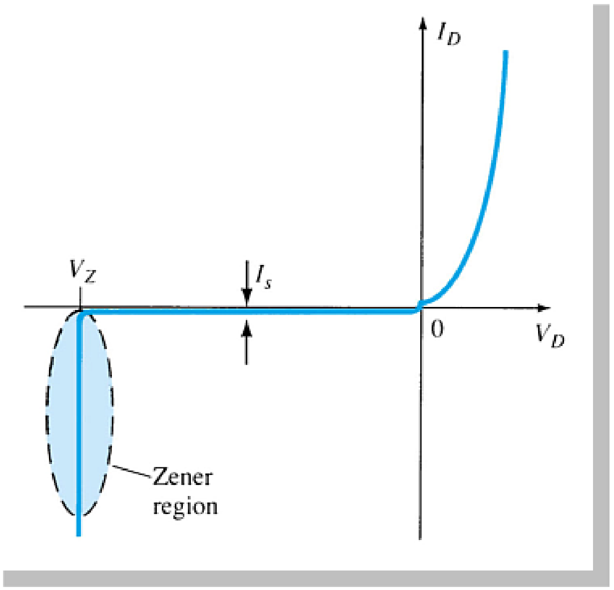
Zener diode
Light-emitting diode
Diode arrays

Zener Diode

A Zener is a diode operated in reverse bias at the Zener voltage (V_Z).

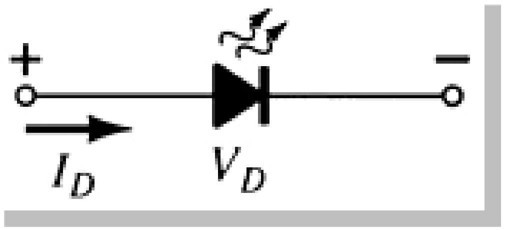
Common Zener voltages are between 1.8 V and 200 V





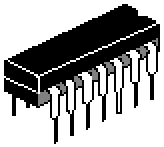
Light-Emitting Diode (LED)

An LED emits photons when it is forward biased.
These can be in the infrared or visible spectrum.
The forward bias voltage is usually in the range of 2 V to 3 V.



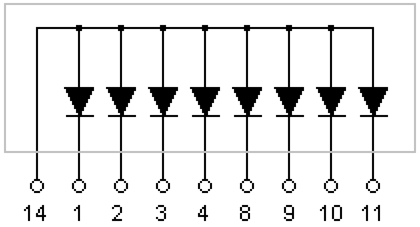
Diode Arrays

Multiple diodes can be packaged together in an integrated circuit (IC).

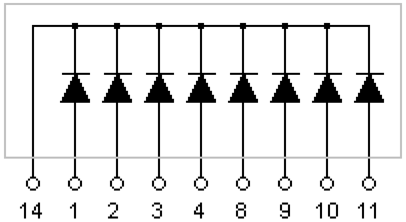


A variety of combinations exist.

Common Anode



Common Cathode



Homework

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