

# ELECTRONIC DEVICES AND CIRCUIT THEORY

TENTH EDITION

BOYLESTAD

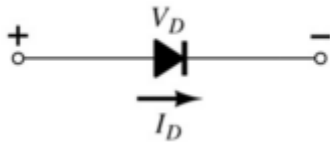


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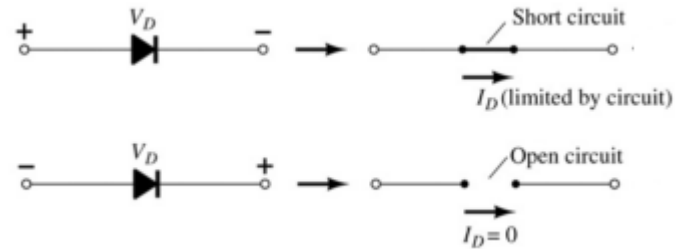
## Chapter 1: Semiconductor Diodes

# Diodes

The diode is a 2-terminal device.

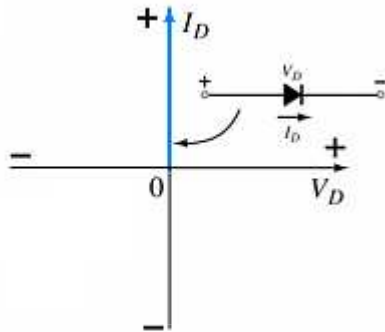


A diode ideally conducts in only one direction.



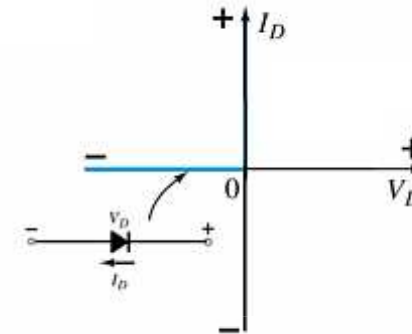
# Diode Characteristics

## 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

# Semiconductor Materials

Materials commonly used in the development of semiconductor devices:

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

# 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

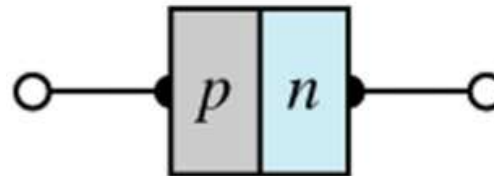
*p*-type

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

# *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.

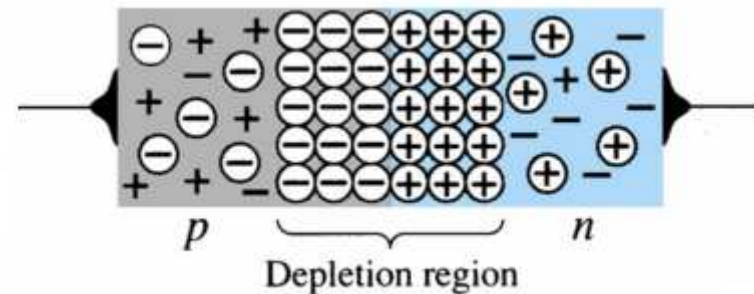


# *p-n* Junctions

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 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.



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

# Diode Operating Conditions

A diode has three operating conditions:

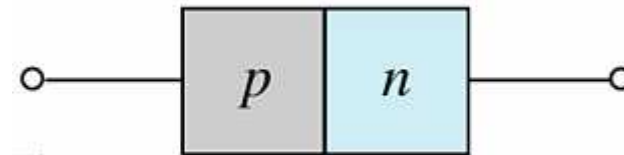
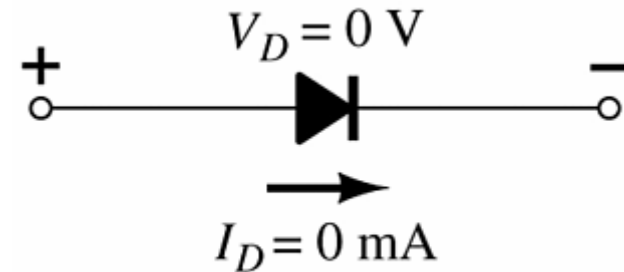
- **No bias**
- **Forward bias**
- **Reverse bias**



# Diode Operating Conditions

## No Bias

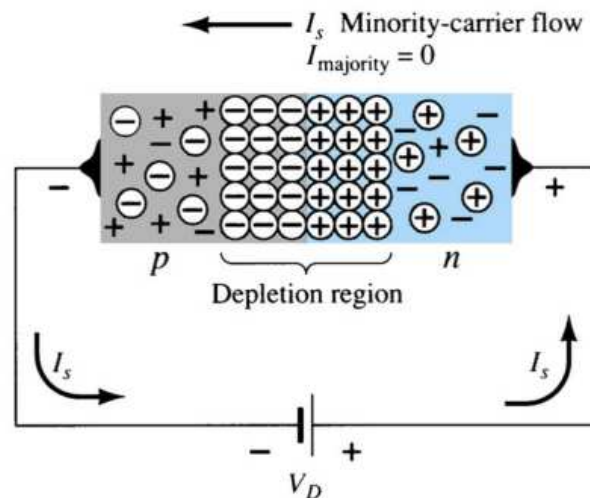
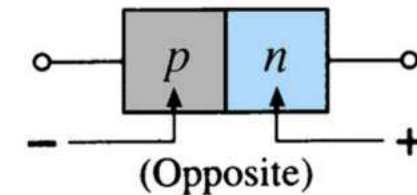
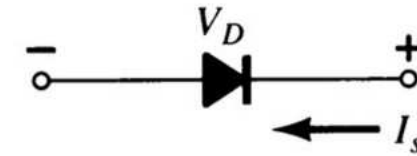
- No external voltage is applied:  $V_D = 0 \text{ V}$
- No current is flowing:  $I_D = 0 \text{ A}$
- Only a modest depletion region exists



# 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.

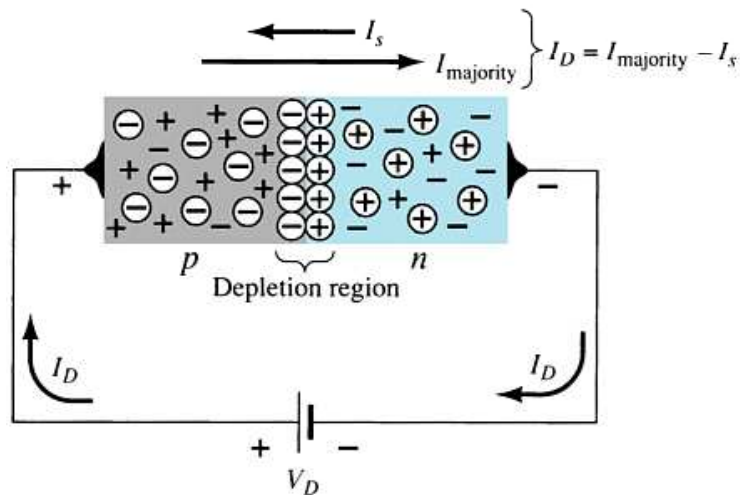
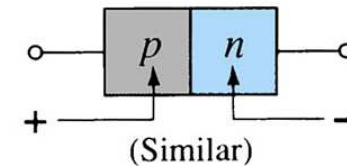
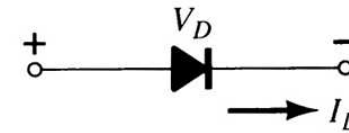


- The reverse voltage causes the depletion region to widen.
- The electrons in the  $n$ -type material are attracted toward the positive terminal of the voltage source.
- The holes in the  $p$ -type material are attracted toward the negative terminal of the voltage source.

# 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.

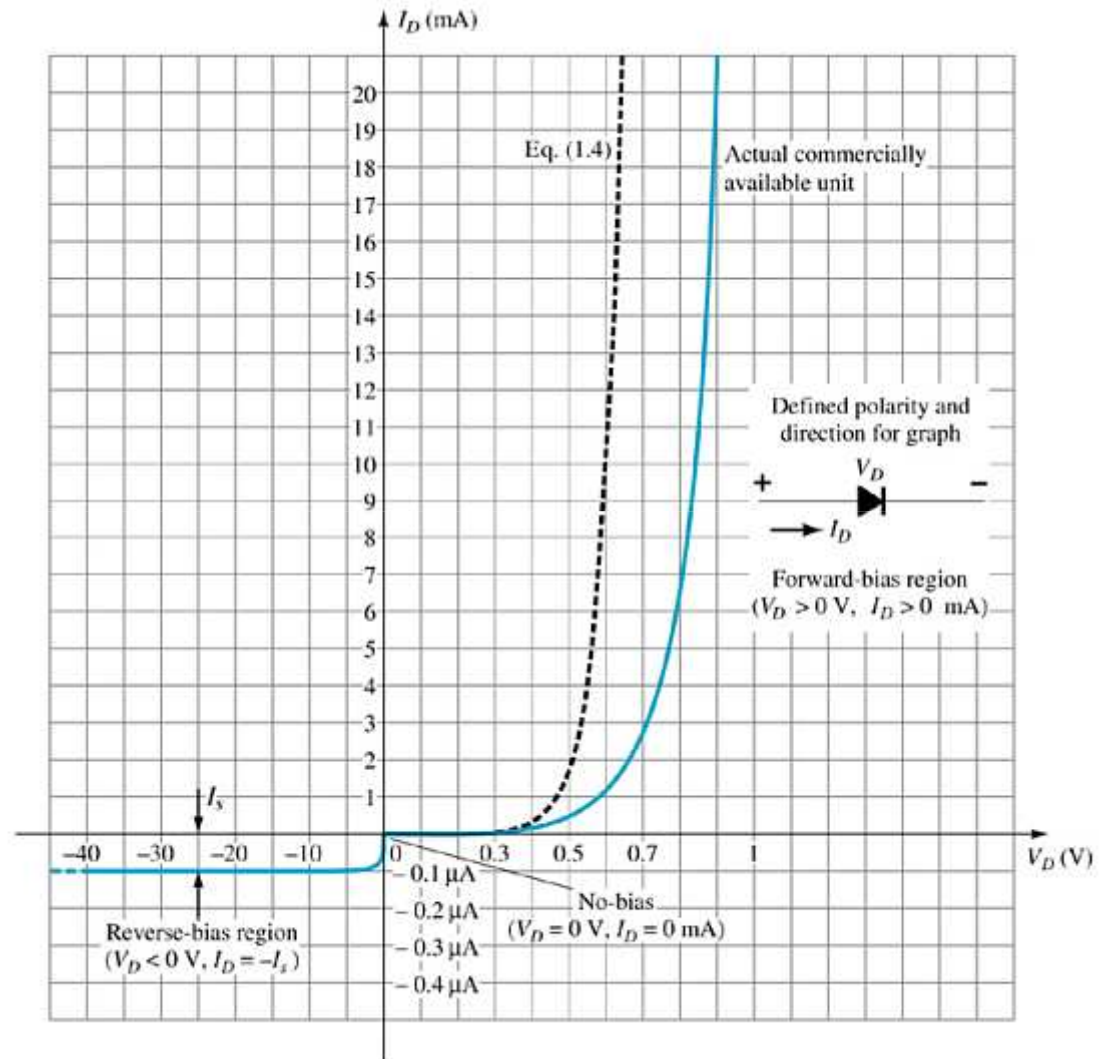


- The forward voltage causes the depletion region to narrow.
- The electrons and holes are pushed toward the  $p$ - $n$  junction.
- The electrons and holes have sufficient energy to cross the  $p$ - $n$  junction.

# Actual Diode Characteristics

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

Carefully note the scale for each of these conditions.



# 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

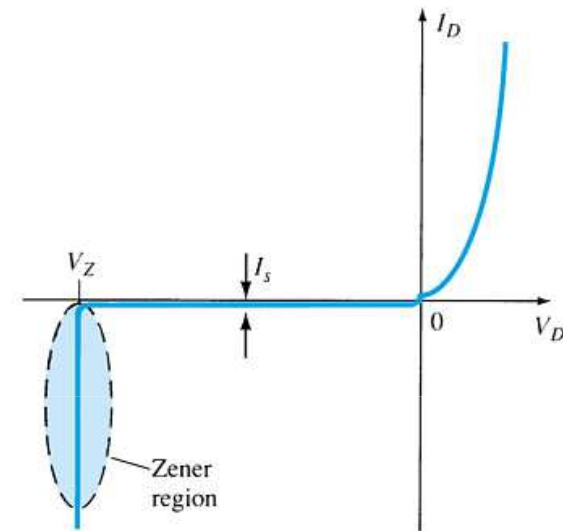
- **The minority carriers in  $n$ -type materials are holes.**
- **The minority carriers in  $p$ -type materials are electrons.**

# 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  $\cong 1.2$  V
- silicon diode  $\cong 0.7$  V
- germanium diode  $\cong 0.3$  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.**



# Resistance Levels

**Semiconductors react differently to DC and AC currents.**

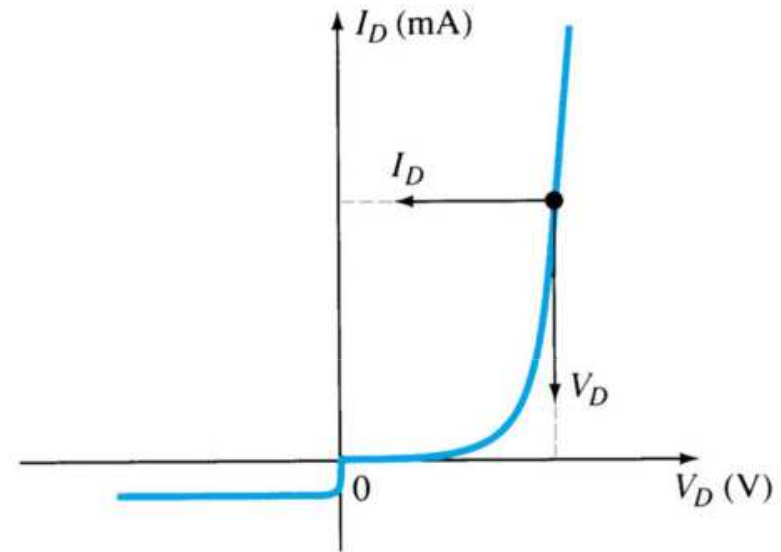
**There are three types of resistance:**

- **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  $\Omega$  for high power devices to 2  $\Omega$  for low power, general purpose diodes. In some cases  $r_B$  can be ignored.**

**In the reverse bias region:**

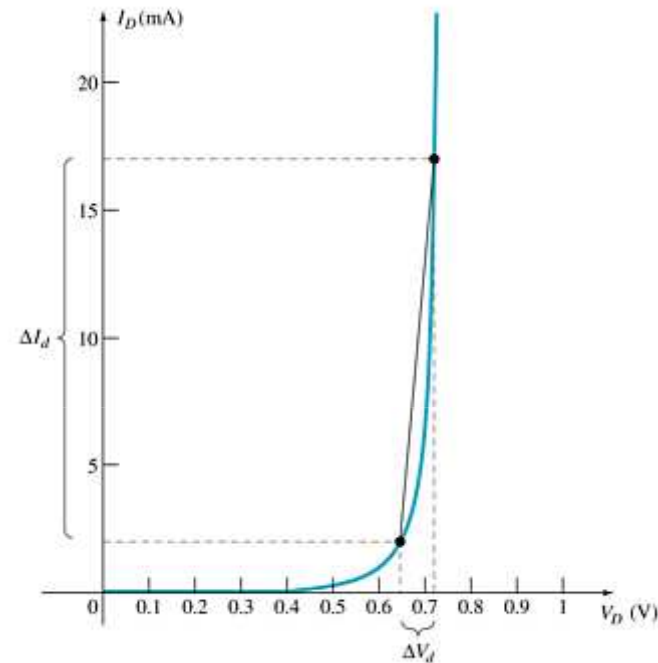
$$r'_d = \infty$$

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

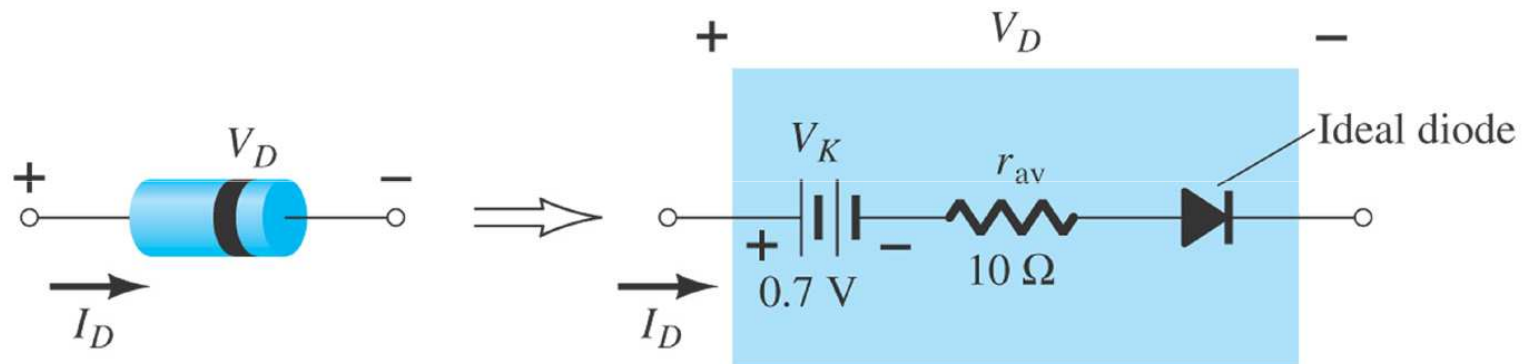
# Average AC Resistance

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

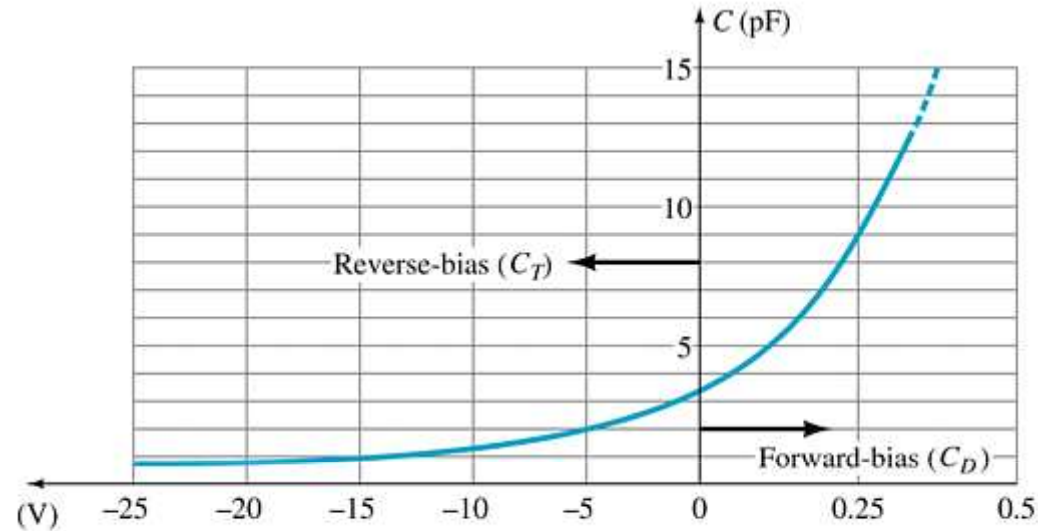
AC resistance can be calculated using the current and voltage values for two points on the diode characteristic curve.



# Diode Equivalent Circuit



# Diode Capacitance

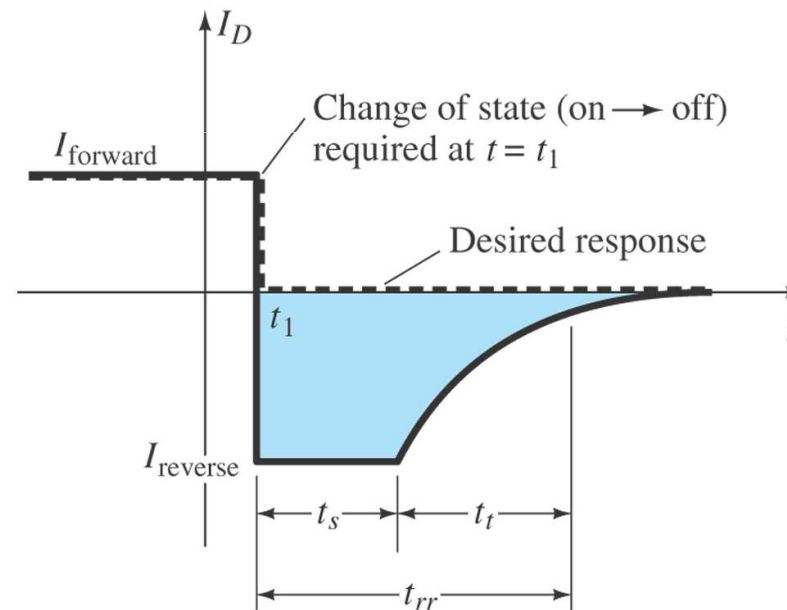


**In reverse bias, the depletion layer is very large. The diode's strong positive and negative polarities create capacitance,  $C_T$ . The amount of capacitance depends on the reverse voltage applied.**

**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.



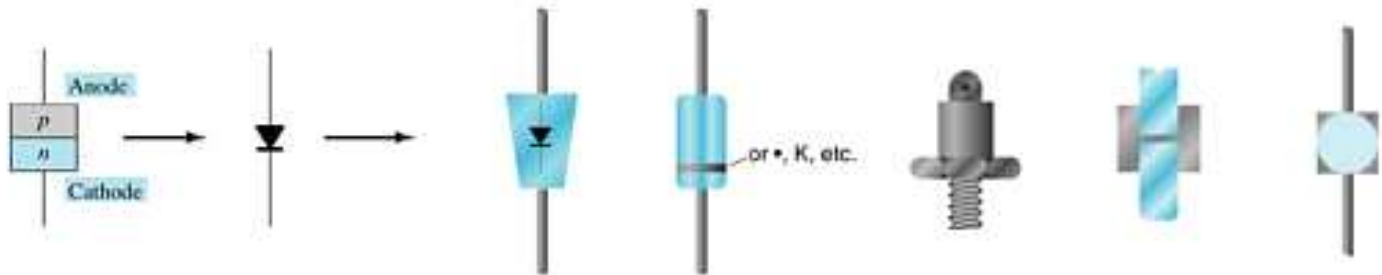
# Diode Specification Sheets

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**

# Diode Testing

Diode checker  
Ohmmeter  
Curve tracer

# Diode Checker

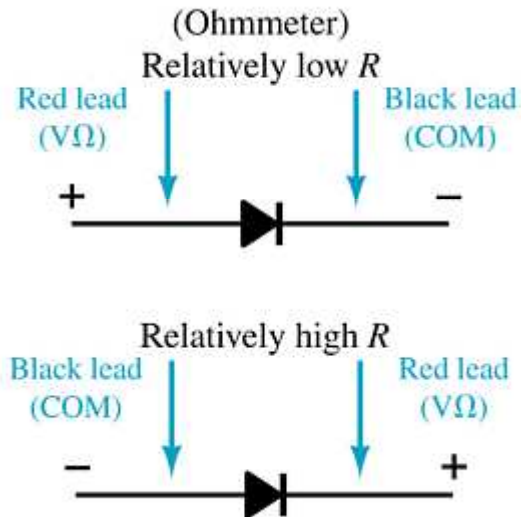
**Many digital multimeters have a diode checking function.  
The diode should be tested out of circuit.**

**A normal diode exhibits its forward voltage:**

- **Gallium arsenide  $\cong 1.2$  V**
- **Silicon diode  $\cong 0.7$  V**
- **Germanium diode  $\cong 0.3$  V**

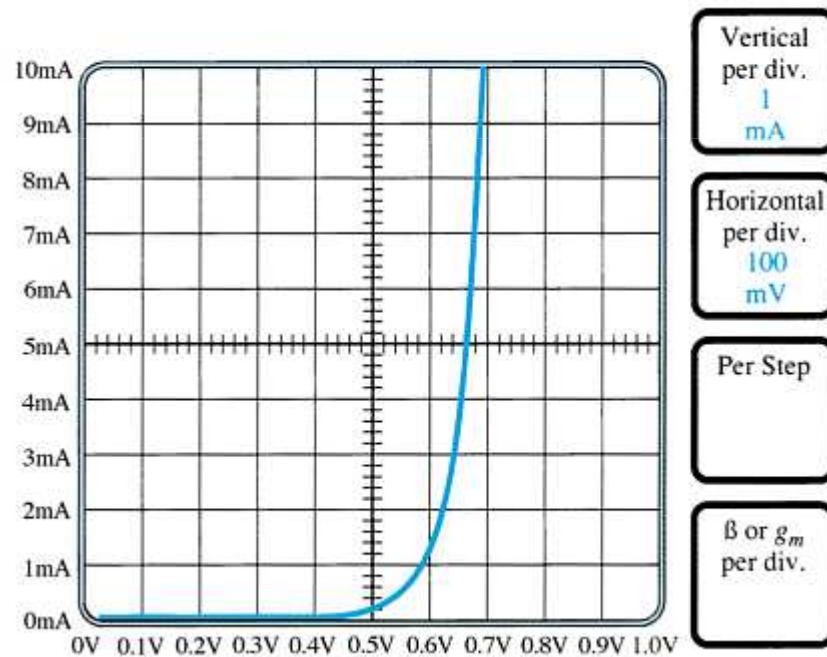
# Ohmmeter

An ohmmeter set on a low Ohms scale can be used to test a diode. The diode should be tested out of circuit.



# Curve Tracer

A curve tracer displays the characteristic curve of a diode in the test circuit. This curve can be compared to the specifications of the diode from a data sheet.



# Other Types of Diodes

**Zener diode**

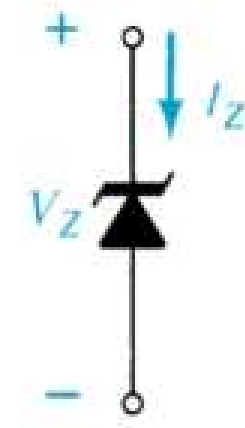
**Light-emitting diode**

**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

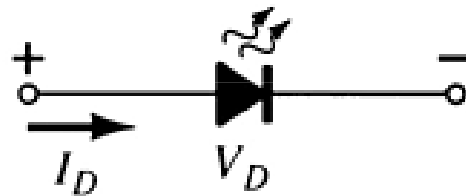


# Light-Emitting Diode (LED)

**An LED emits photons when it is forward biased.**

**These can be in the infrared or visible spectrum.**

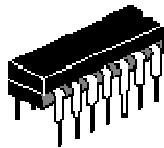
**The forward bias voltage is usually in the range of 2 V to 3 V.**





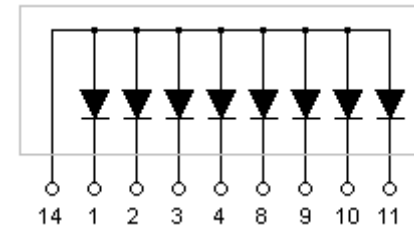
# Diode Arrays

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



A variety of combinations exist.

Common Anode



Common Cathode

