Electronic Circuits

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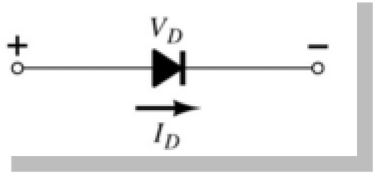
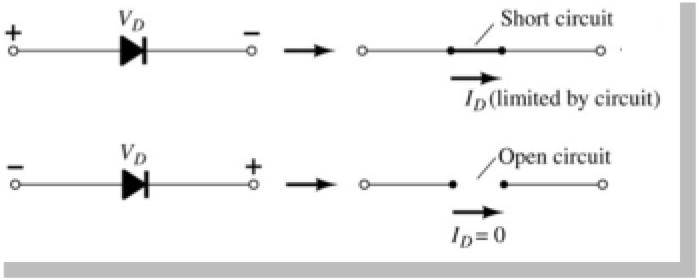
Diodes

The diode is a 2-terminal device.

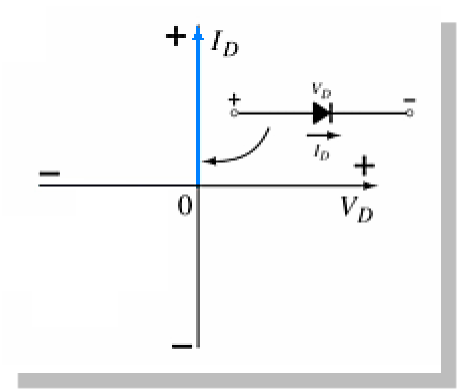


A diode ideally conducts in only one direction.



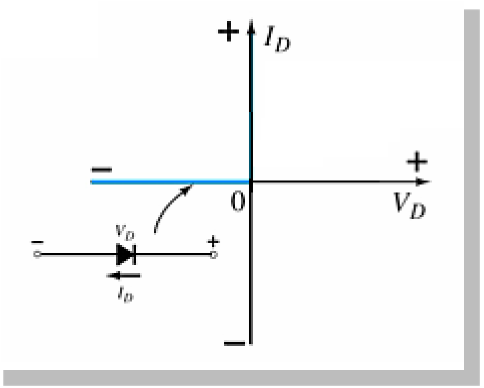
Diode Characteristics

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:

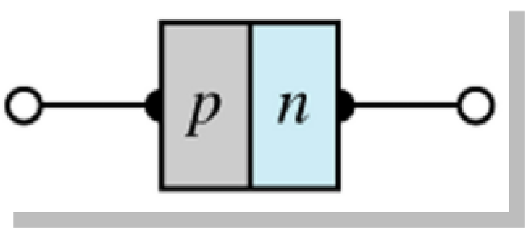
***n*-type**
***p*-type**

- ***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**.

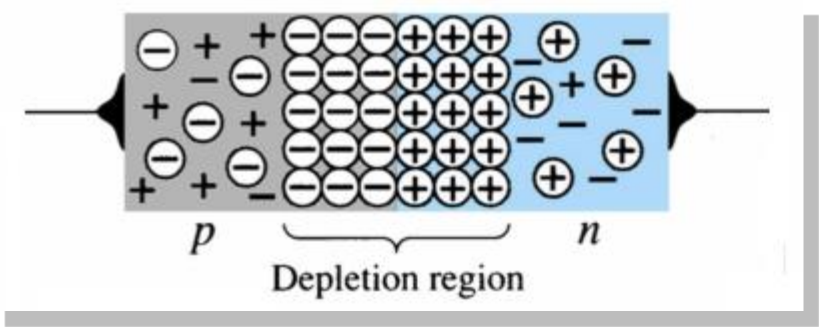


p-n Junctions

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.



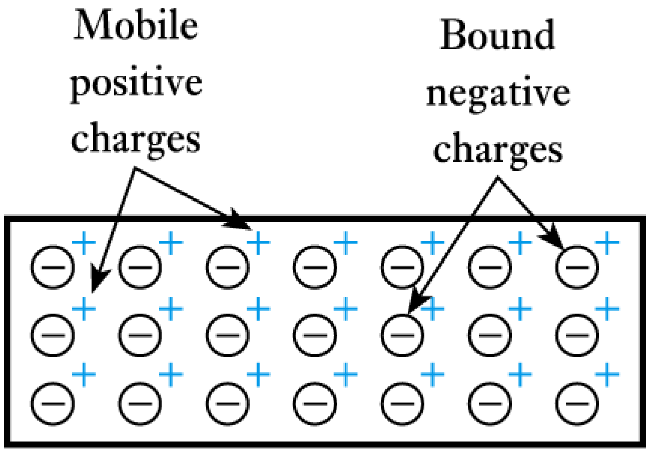
The result is the formation of a **depletion region** around the junction.

Doping of semiconductors

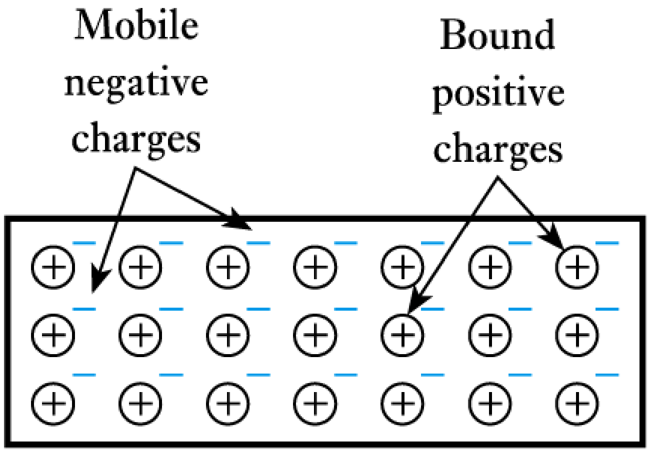
- **Doping**
  - the addition of small amounts of impurities drastically affects its properties
  - some materials form an excess of *electrons* and produce an ***n*-type semiconductor**
  - some materials form an excess of *holes* and produce a ***p*-type semiconductor**
  - both *n*-type and *p*-type materials have much greater conductivity than pure semiconductors
  - this is **extrinsic conduction.**

Doping of semiconductors (contd.)

- The dominant charge carriers in a doped semiconductor (e.g. electrons in *n*-type material) are called **majority charge carriers**. The other type are **minority charge carriers.**
- The overall doped material is electrically neutral.



(a) *p*-type semiconductor



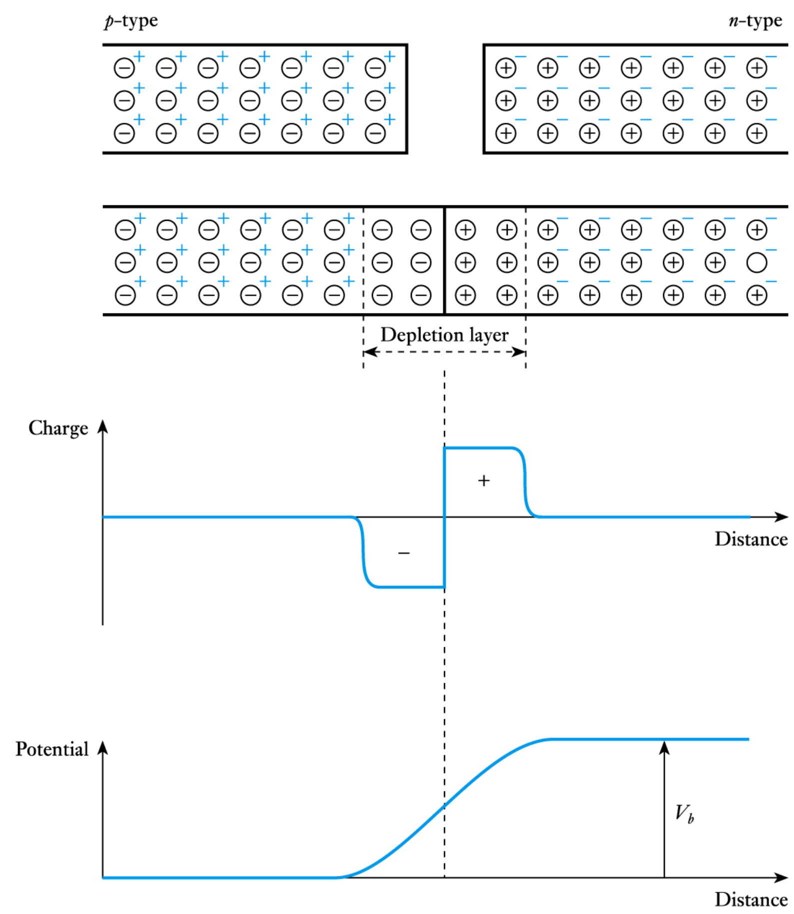
(b) *n*-type semiconductor

pn Junctions

- When *p*-type and *n*-type materials are joined, this forms a ***pn* junction**
  - the majority charge carriers on each side diffuse across the junction where they combine with (and remove) the charge carriers of the opposite polarity.
  - hence, around the junction there are few free charge carriers and we have a **depletion layer** (also called a **space-charge layer**).

pn Junctions (contd.)

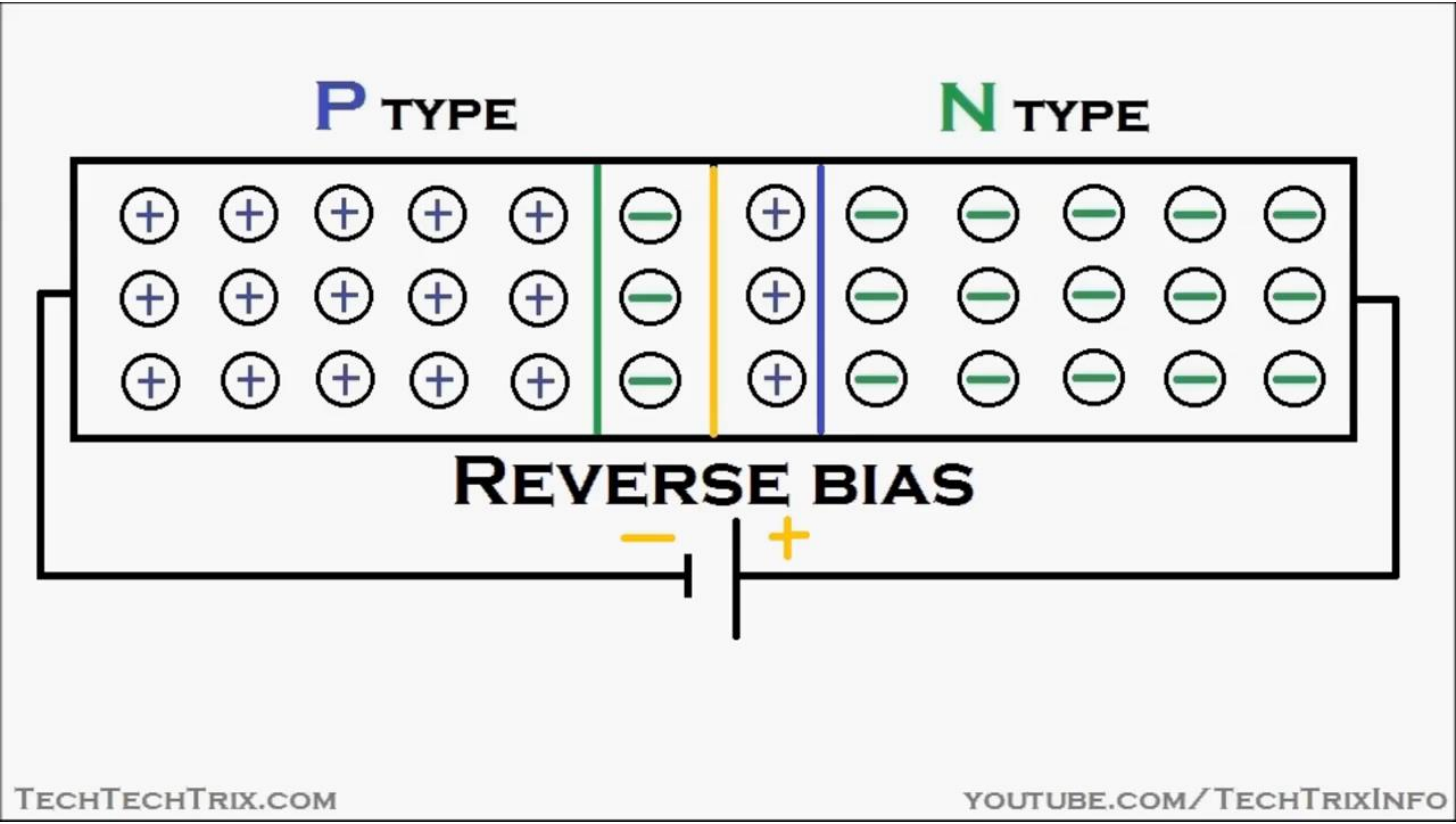
- The diffusion of positive charge in one direction and negative charge in the other produces a charge imbalance
  - this results in a **potential barrier** across the junction.



pn Junctions (contd.)

- **Potential barrier**
  - the barrier opposes the flow of *majority* charge carriers and only a small number have enough energy to surmount it.
    - This generates a small **diffusion current.**
  - the barrier encourages the flow of *minority* carriers and any that come close to it will be swept over
    - This generates a small **drift current.**
  - for an isolated junction these two currents must balance each other and the net current is zero.

pn Junctions (contd.)



pn Junctions (contd.)

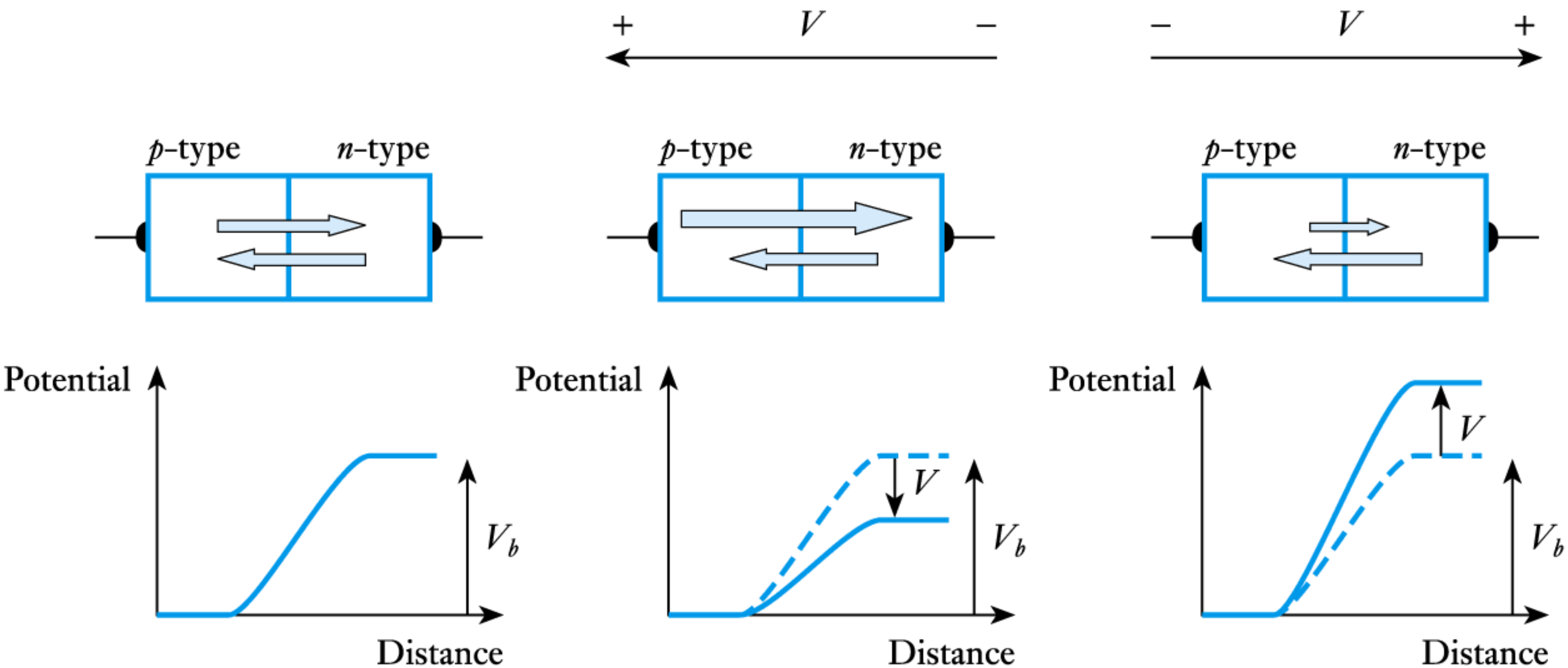
- **Forward bias**
  - if the *p*-type side is made *positive* with respect to the *n*-type side the height of the barrier is reduced
  - more majority charge carriers have sufficient energy to surmount it
  - the diffusion current therefore increases while the drift current remains the same
  - there is thus a net current flow across the junction which increases with the applied voltage.

pn Junctions (contd.)

- **Reverse bias**
  - if the *p*-type side is made *negative* with respect to the *n*-type side the height of the barrier is increased
  - the number of majority charge carriers that have sufficient energy to surmount it rapidly decreases
  - the diffusion current therefore vanishes while the drift current remains the same
  - thus the only current is a small leakage current caused by the (approximately constant) drift current
  - the leakage current is usually negligible (a few nA).

pn Junctions (contd.)

- **Currents in a *pn* junction**



(a) An isolated junction (b) Forward bias (c) Reverse bias

pn Junctions (contd.)

- **Forward and reverse currents**
  - *pn* junction current is given approximately by

$$I = I_S\left(\exp\frac{eV}{\eta kT} - 1\right)$$

  - where *I* is the current, *e* is the electronic charge, *V* is the applied voltage, *k* is Boltzmann's constant, *T* is the absolute temperature and η (Greek letter *eta*) is a constant in the range 1 to 2 determined by the junction material
  - for most purposes we can assume $\eta = 1$.

pn Junctions (contd.)

- Thus,

$$I \approx I_S\left(\exp\frac{eV}{kT} - 1\right)$$

at room temperature $e/kT \sim 40\ \mathrm{V}^{-1}$

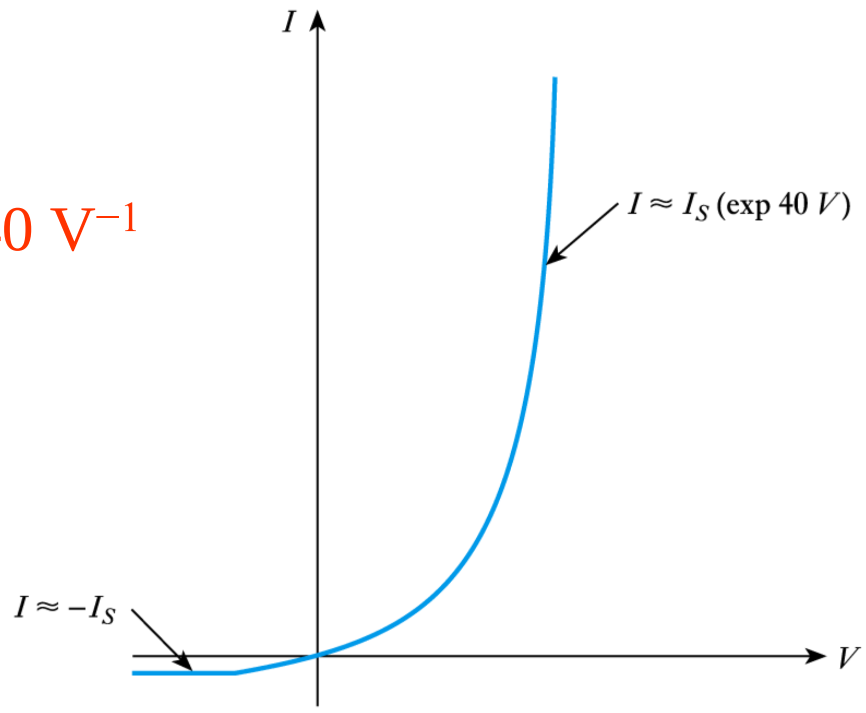
- If $V > +\,0.1$ V,

$$I \approx I_s\left(\exp\frac{eV}{kT}\right) = I_s\left(\exp 40V\right)$$

- If $V < -\,0.1$ V,

$$I \approx I_s(0-1) = -I_s$$

– I_S is the **reverse saturation current.**



Diode Operating Conditions

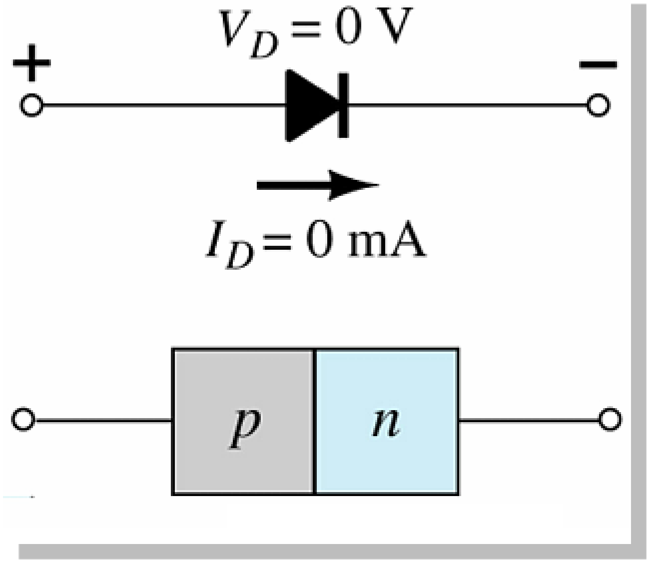
A diode has three operating conditions:

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

Diode Operating Conditions

No Bias

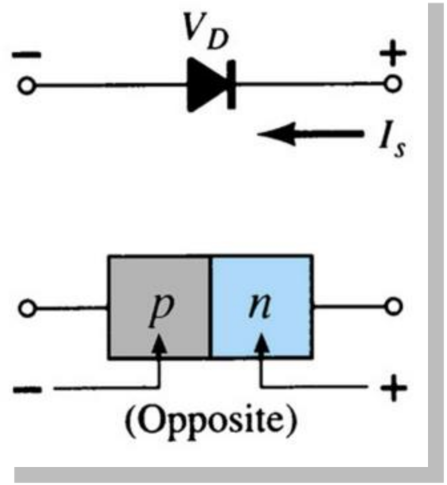
- **No external voltage is applied: V_D = 0 V**
  - **No current is flowing: I_D = 0 A**
- **Only a modest depletion region exists**

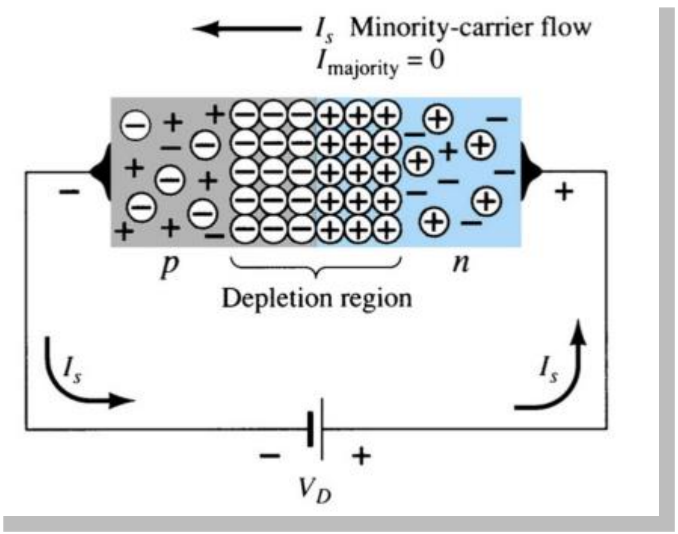


Diode Operating Conditions

Reverse Bias

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



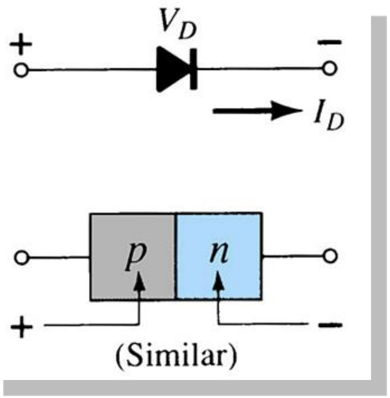


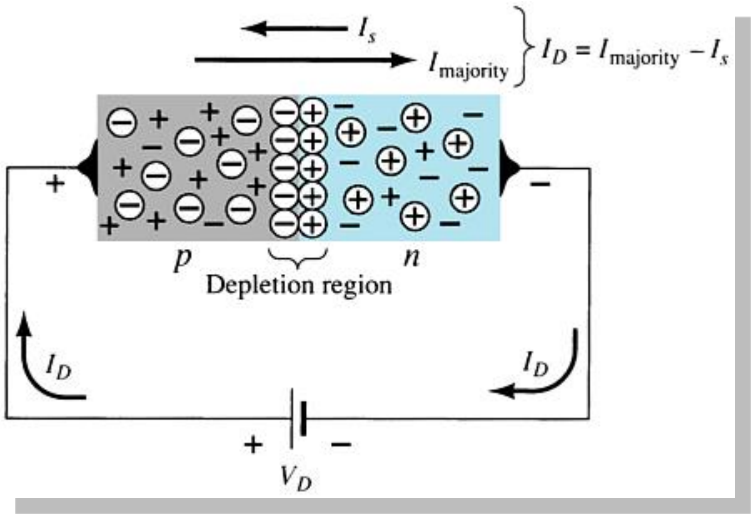
- **The reverse voltage causes the depletion region to widen.**
- **The electrons in the *n*-type material are attracted toward the positive terminal of the voltage source.**
- **The holes in the *p*-type material are attracted toward the negative terminal of the voltage source.**

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.



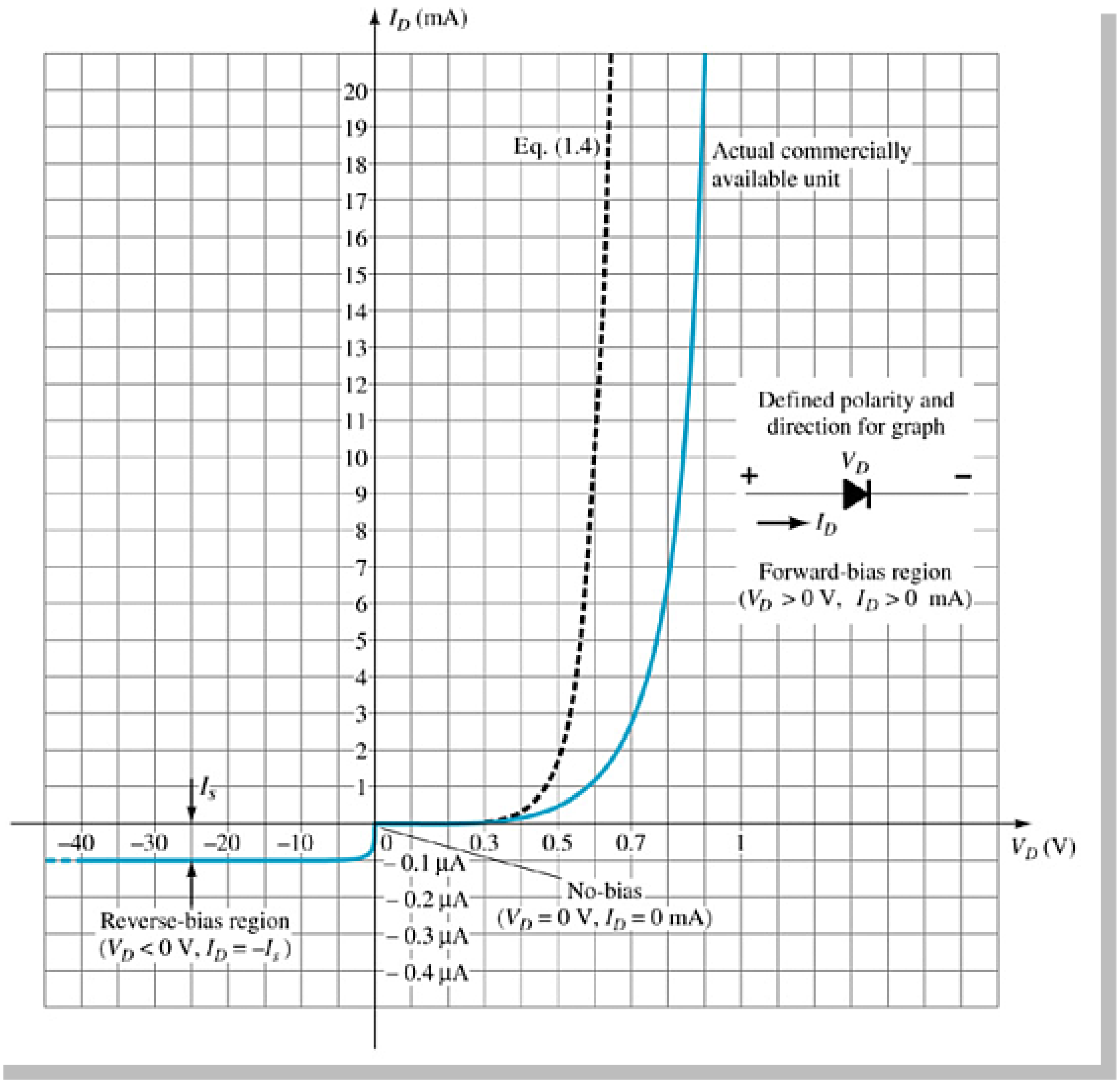


- The forward voltage causes the depletion region to narrow.
- The electrons and holes are pushed toward the *p-n* junction.
- The electrons and holes have sufficient energy to cross the *p-n* junction.

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

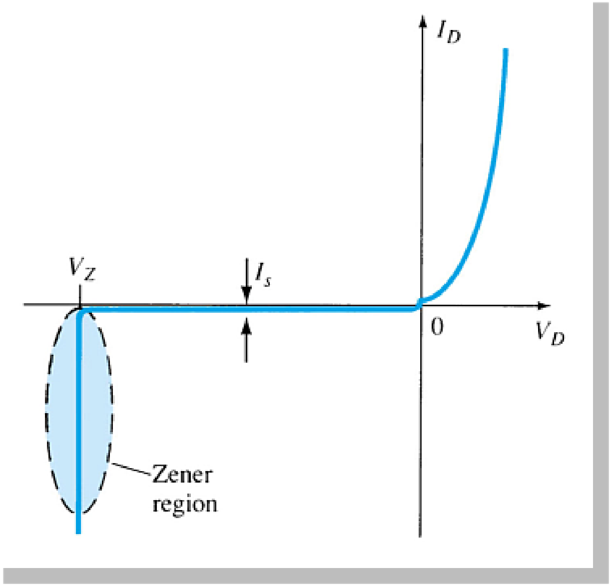
- **The minority carriers in *n*-type materials are holes.**
- **The minority carriers in *p*-type materials are electrons.**

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 ≅ 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.

Resistance Levels

Semiconductors react differently to DC and AC currents.

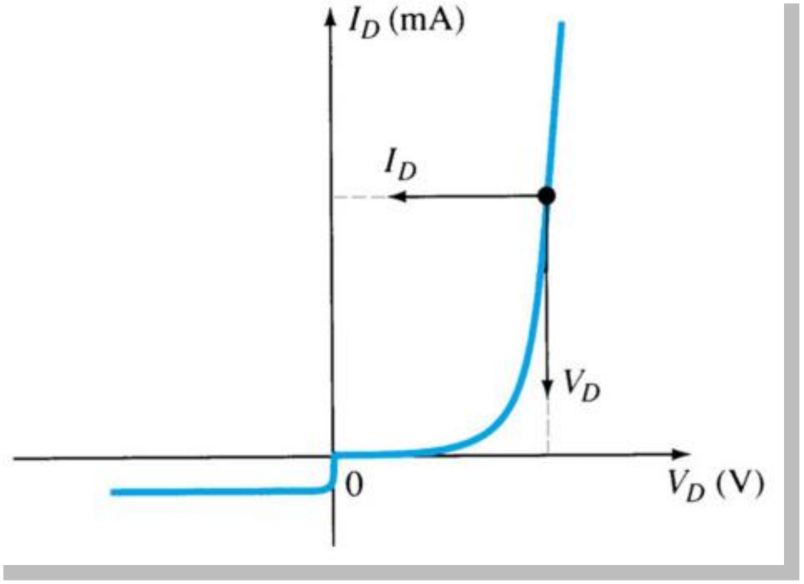
There are three types of resistance:

- 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:

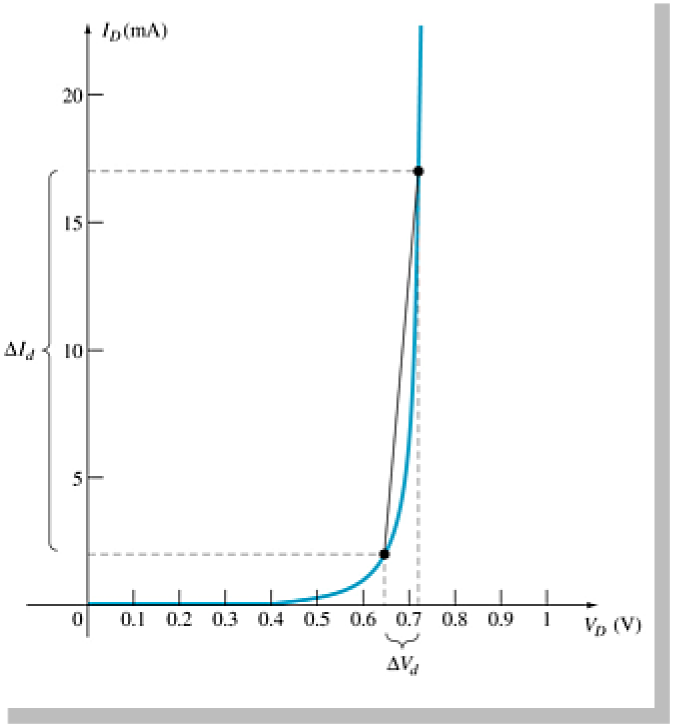
$$\mathrm{r'_d} = \infty$$

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

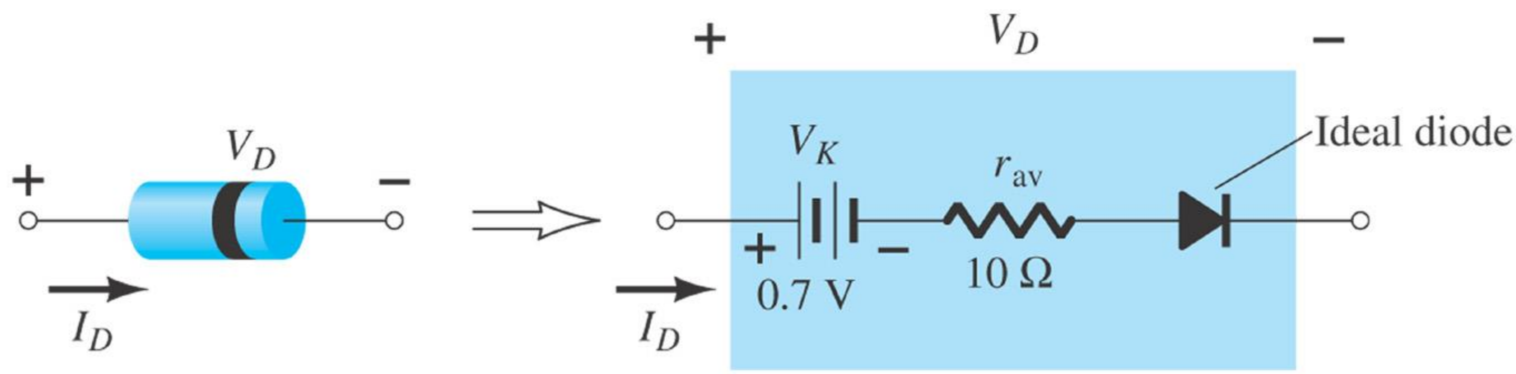
Average AC Resistance

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

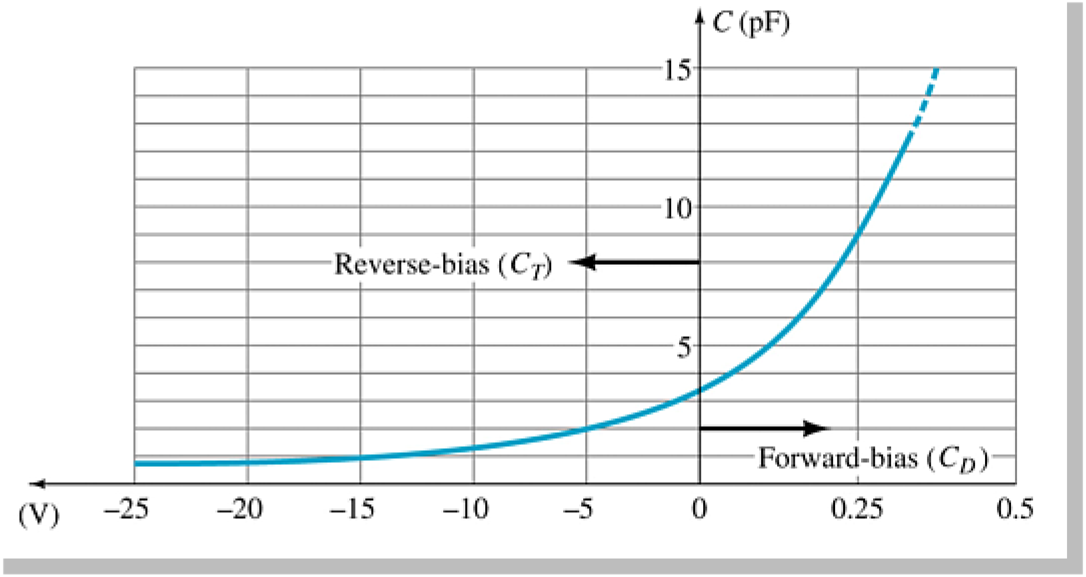
AC resistance can be calculated using the current and voltage values for two points on the diode characteristic curve.



Diode Equivalent Circuit



Diode Capacitance

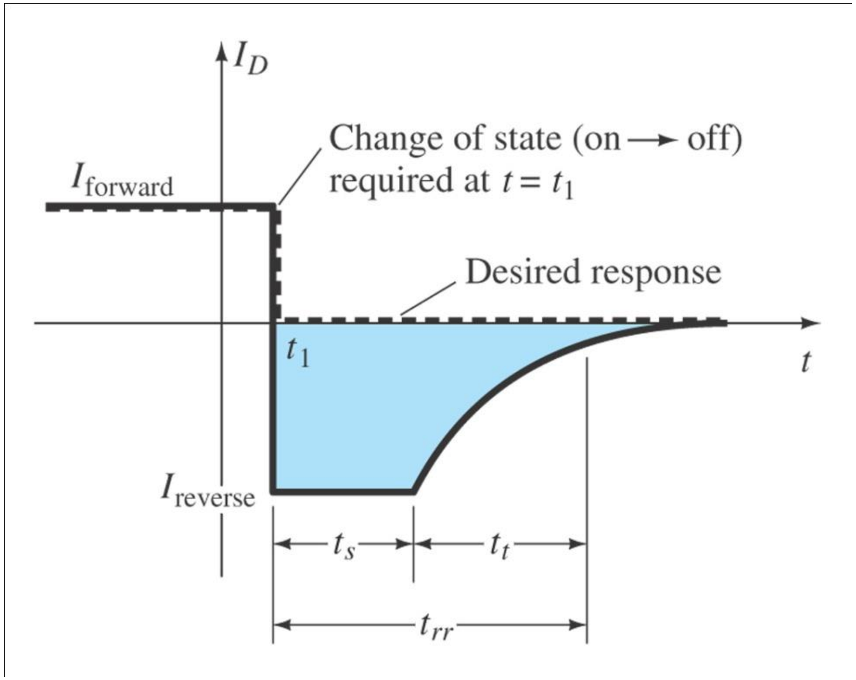


In reverse bias, the depletion layer is very large. The diode's strong positive and negative polarities create capacitance, C_T. The amount of capacitance depends on the reverse voltage applied.

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.

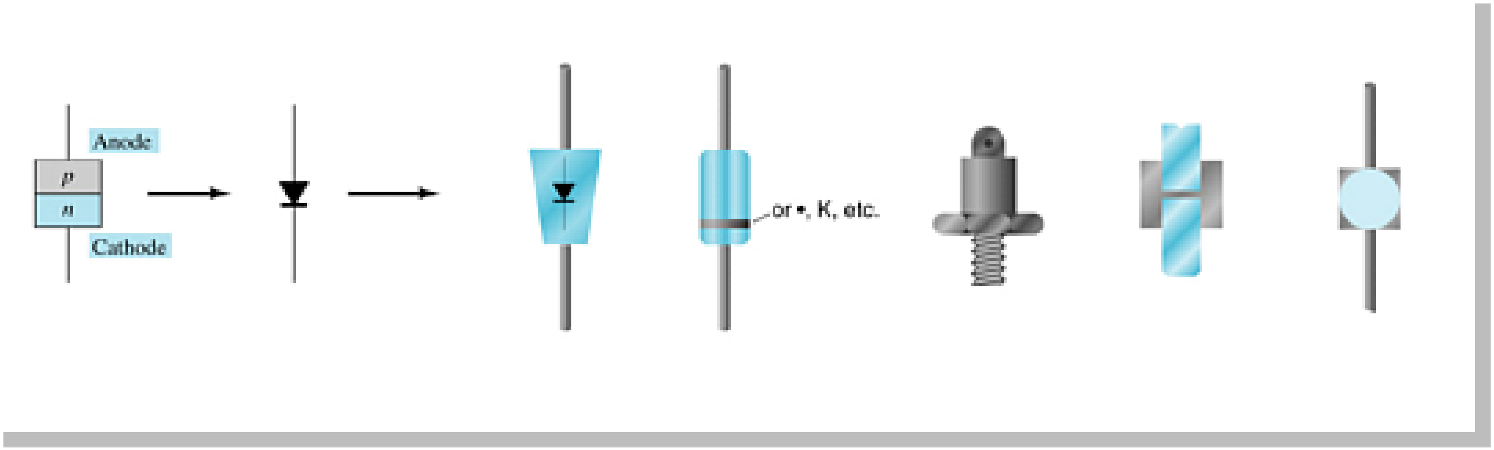


Diode Specification Sheets

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

Diode Testing

Diode checker
Ohmmeter
Curve tracer

Diode Checker

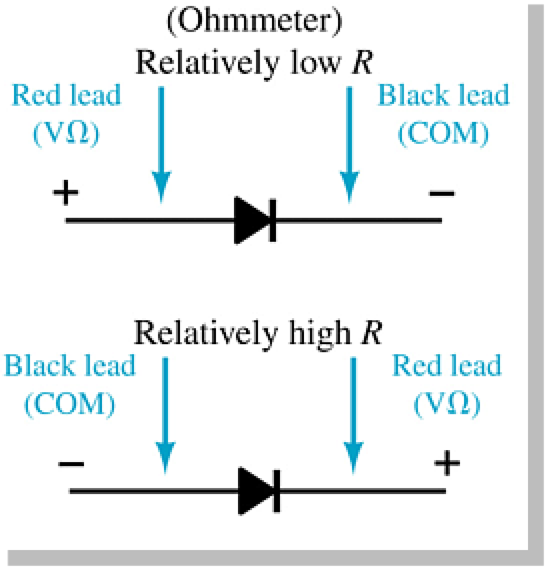
Many digital multimeters have a diode checking function. The diode should be tested out of circuit.

A normal diode exhibits its forward voltage:

- Gallium arsenide ≅ 1.2 V
- Silicon diode ≅ 0.7 V
- Germanium diode ≅ 0.3 V

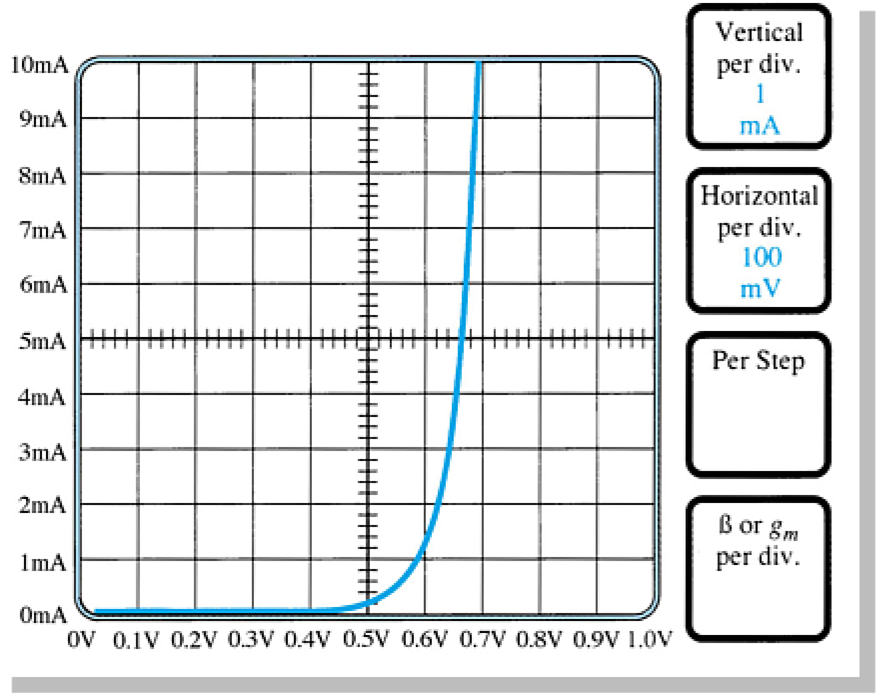
Ohmmeter

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.



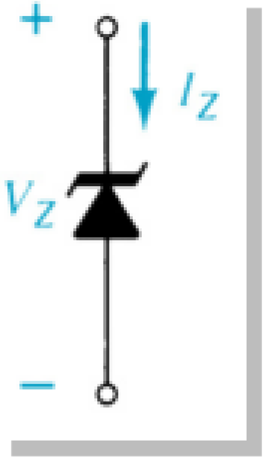
Other Types of Diodes

Zener diode
Light-emitting diode
Diode arrays

Zener Diode

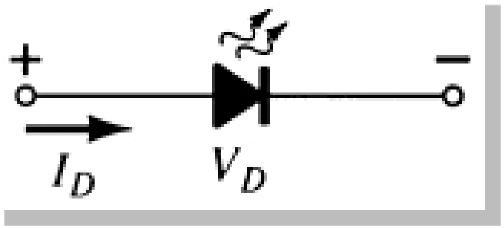
A Zener is a diode operated in reverse bias at the Zener voltage (V_Z).

Common Zener voltages are between 1.8 V and 200 V



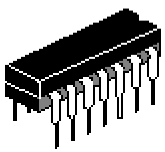
Light-Emitting Diode (LED)

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.



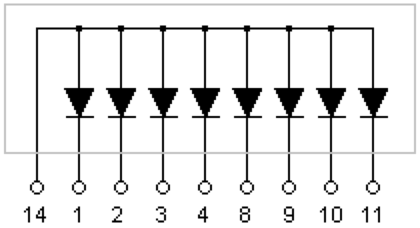
Diode Arrays

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



A variety of combinations exist.

Common Anode



Common Cathode