Semiconductor Diodes

Categories of Solids

- There are three categories of solids, based on their **conducting properties**:
  - conductors
  - semiconductors
  - insulators

Electrical Resistivity and Conductivity of Selected Materials at 293 K

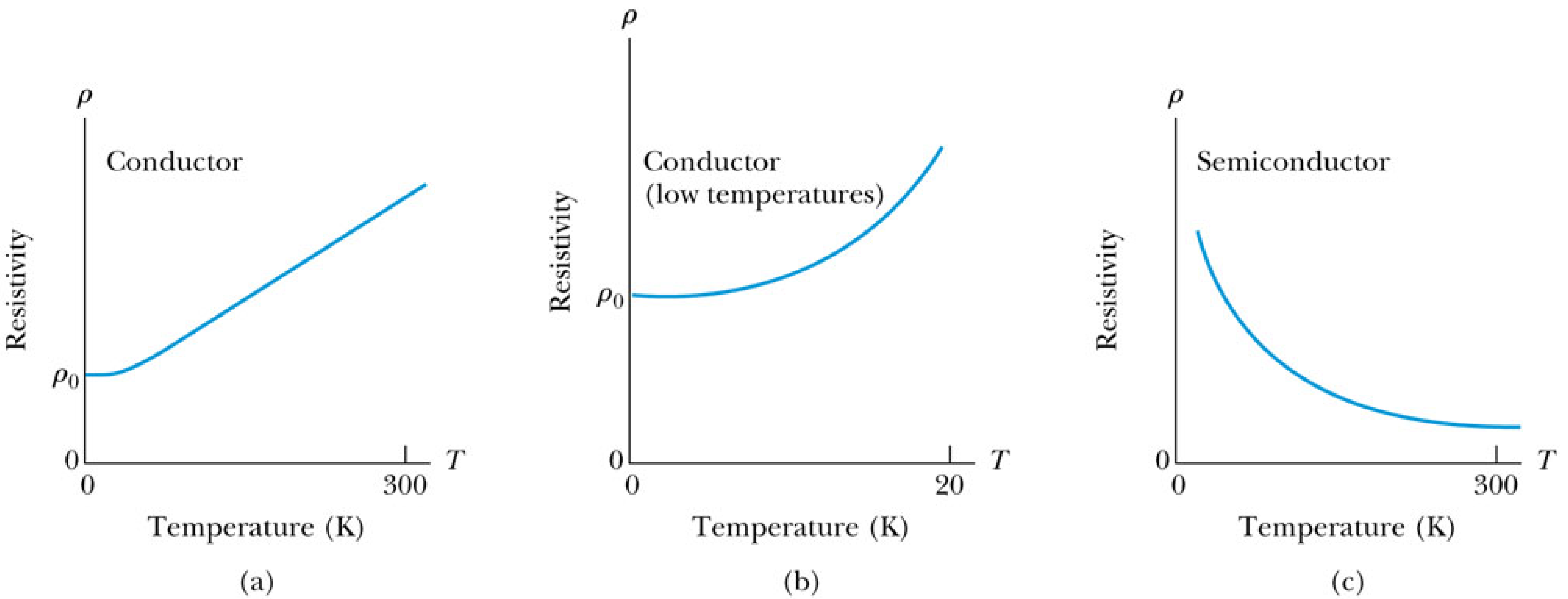
Table 11.1 Electrical Resistivity and Conductivity of Selected Materials at 293 K

Material	Resistivity ($\Omega \cdot m$)	Conductivity ($\Omega^{-1} \cdot m^{-1}$)
Metals		
Silver	1.59×10^{-8}	6.29×10^{7}
Copper	1.72×10^{-8}	5.81×10^{7}
Gold	2.44×10^{-8}	4.10×10^{7}
Aluminum	2.82×10^{-8}	3.55×10^{7}
Tungsten	5.6×10^{-8}	1.8×10^{7}
Platinum	1.1×10^{-7}	9.1×10^{6}
Lead	2.2×10^{-7}	4.5×10^{6}
Alloys		
Constantan	4.9×10^{-7}	2.0×10^{6}
Nichrome	1.5×10^{-6}	6.7×10^{5}
Semiconductors		
Carbon	3.5×10^{-5}	2.9×10^{4}
Germanium	0.46	2.2
Silicon	640	1.6×10^{-3}
Insulators		
Wood	10^{8}–10^{11}	10^{-8}–10^{-11}
Rubber	10^{13}	10^{-13}
Amber	5×10^{14}	2×10^{-15}
Glass	10^{10}–10^{14}	10^{-10}–10^{-14}
Quartz (fused)	7.5×10^{17}	1.3×10^{-18}

Reviewing the previous table reveals that:

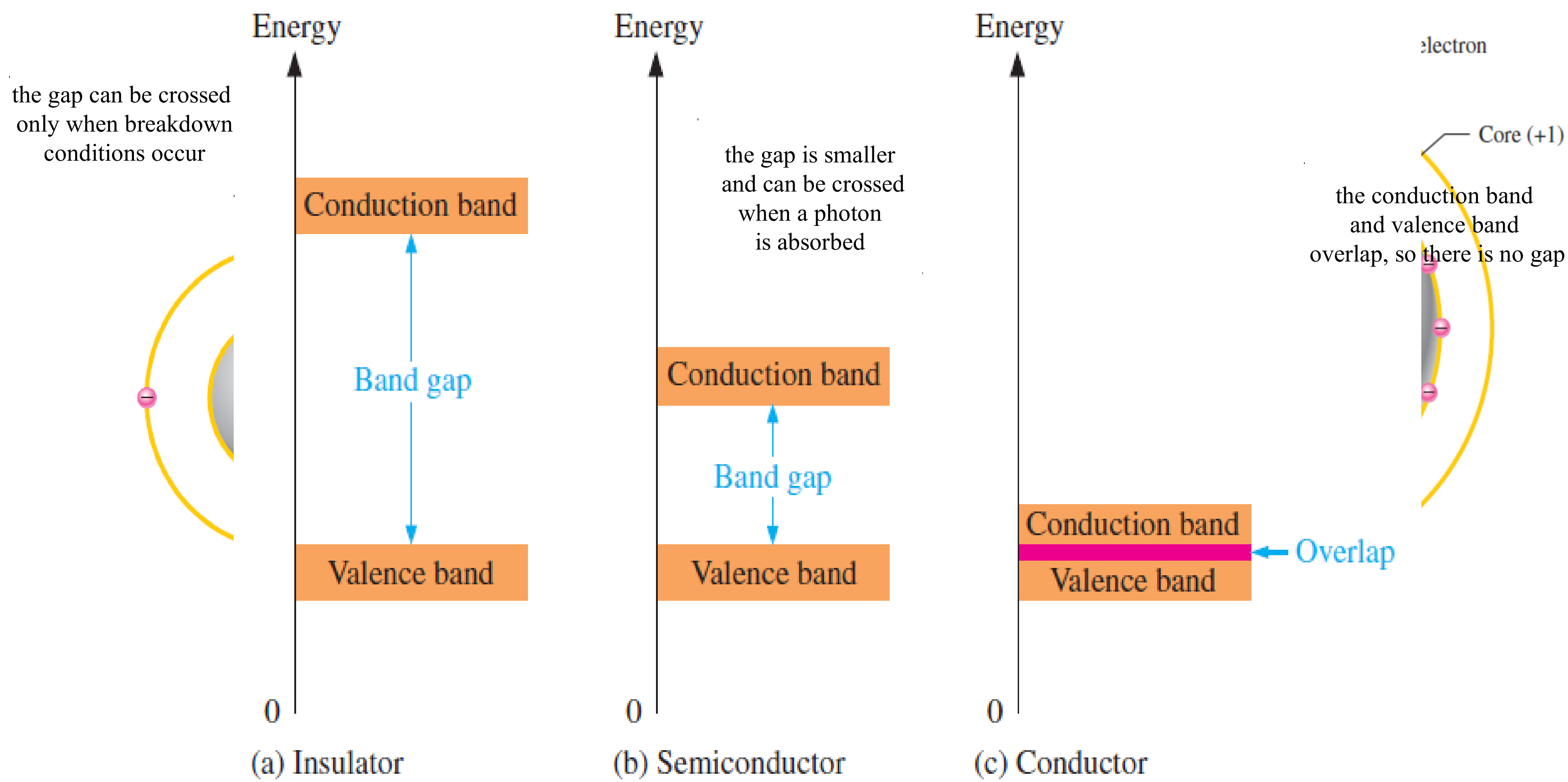
- The electrical conductivity at room temperature is quite different for each of these three kinds of solids
  - **Metals and alloys** have the highest conductivities
  - followed by **semiconductors**
  - and then by **insulators**

Resistivity vs. Temperature



Resistivity versus temperature for a typical conductor. Notice the linear rise in resistivity with increasing temperature at all but very low temperatures. (b) Resistivity versus temperature for a typical conductor at very low temperatures. Notice that the curve flattens and approaches a nonzero resistance as $T \to 0$. (c) Resistivity versus temperature for a typical semiconductor. The resistivity increases dramatically as $T \to 0$.

Conductor and Insulators.
Atomic Model



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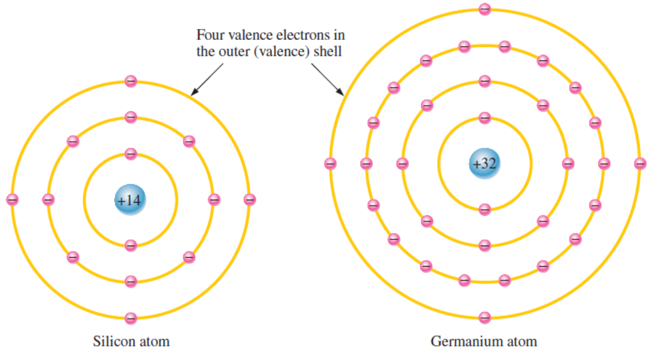
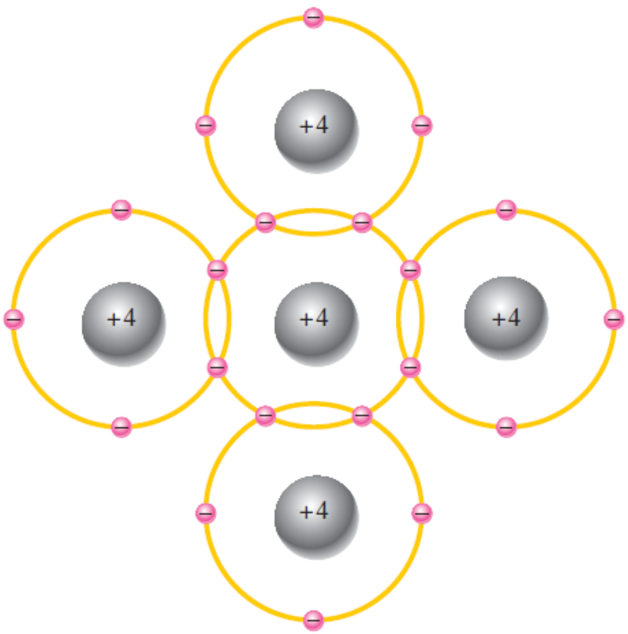
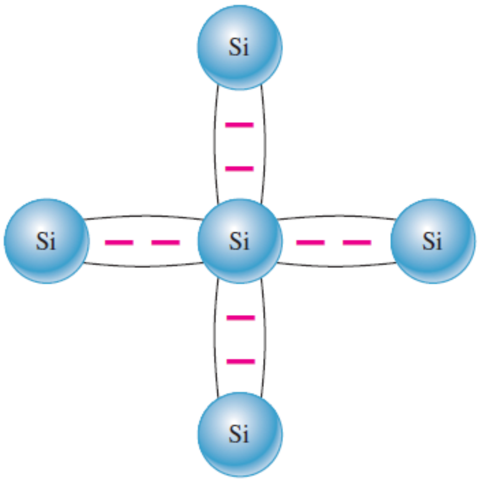
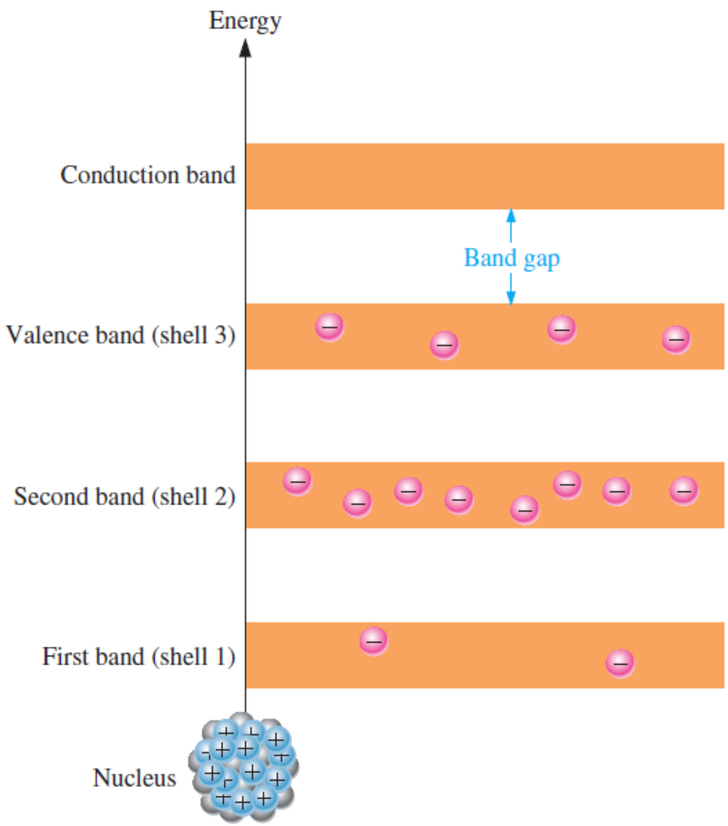
Silicon and Germanium

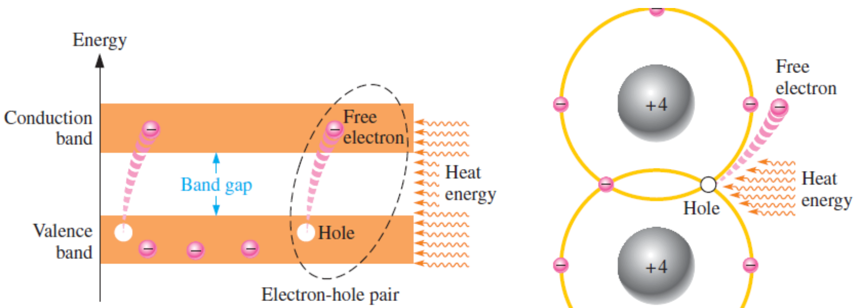






Conduction Electron and Holes.





(a) Energy diagram

(b) Bonding diagram

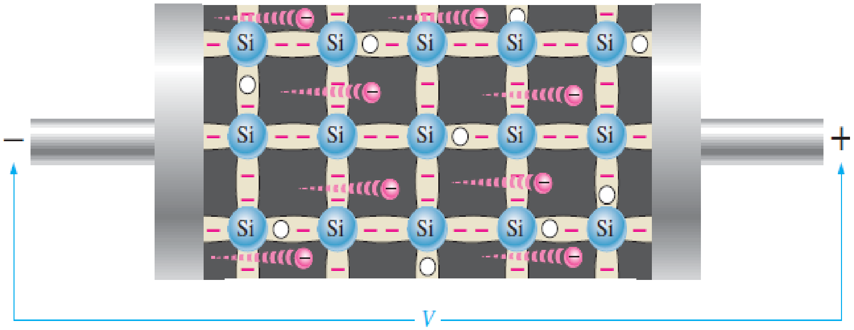
An intrinsic (pure) silicon crystal at room temperature has sufficient heat energy for some valence electrons to jump the gap from the valence band into the conduction band, becoming free electron called '**Conduction Electron**'

It leaves a vacancy in valance band, called **hole**.

Recombination occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

Electron Hole Current.

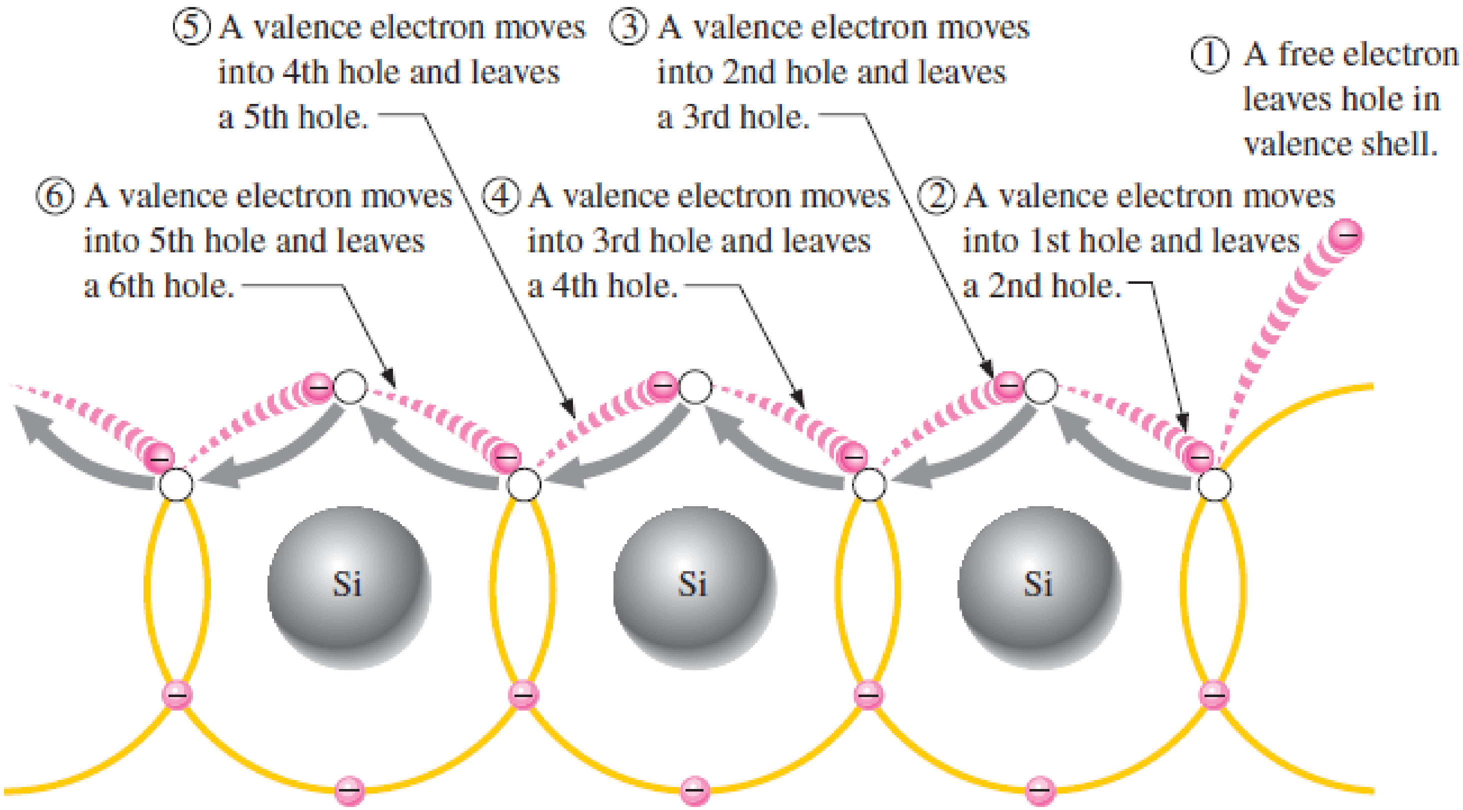
In conduction band : When a voltage is applied across a piece of intrinsic silicon, the thermally generated free electrons in the conduction band, are now easily attracted toward the positive end.



This movement of free electrons is one type of current in a semiconductive material and is called ***electron current.***

In valance band: In valance band holes generated due to free electrons. Electrons in the valance band are although still attached with atom and not free to move, however they can move into nearby hole with a little change in energy, thus leaving another hole where it came from. Effectively the hole has moved from one place to another in the crystal structure. It is called ***hole current.***

Electron Hole Current.



When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.

Band Theory of Solids

- In order to account for *decreasing* resistivity with increasing temperature as well as other properties of semiconductors, a new theory known as the **band theory** is introduced.

- The essential feature of the band theory is that the allowed energy states for electrons are nearly continuous over certain ranges, called **energy bands**, with forbidden energy gaps between the bands.

Band Theory and Conductivity

- Band theory helps us understand what makes a conductor, insulator, or semiconductor.
  1) Good conductors like copper can be understood using the free electron
  2) It is also possible to make a conductor using a material with its highest band filled, in which case no electron in that band can be considered free.
  3) If this filled band overlaps with the next higher band, however (so that effectively there is no gap between these two bands) then an applied electric field can make an electron from the filled band jump to the higher level.
- This allows conduction to take place, although typically with slightly higher resistance than in normal metals. Such materials are known as **semimetals**.

Valence and Conduction Bands

- The band structures of insulators and semiconductors resemble each other qualitatively. Normally there exists in both insulators and semiconductors a filled energy band (referred to as the **valence band**) separated from the next higher band (referred to as the **conduction band**) by an energy gap.

- If this gap is at least several electron volts, the material is an **insulator.** It is too difficult for an applied field to overcome that large an energy gap, and thermal excitations lack the energy to promote sufficient numbers of electrons to the **conduction band.**

Smaller energy gaps create **semiconductors**

- For energy gaps smaller than about 1 electron volt, it is possible for enough electrons to be excited thermally into the conduction band, so that an applied electric field can produce a modest current.

  The result is a semiconductor.

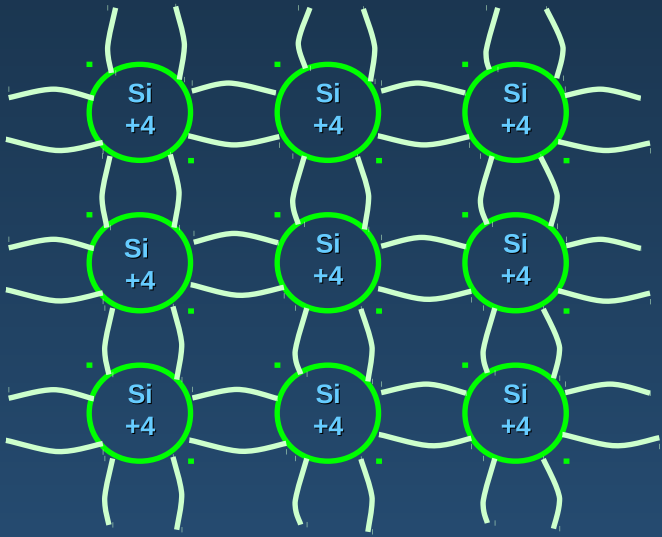
Types of Semiconductor

Intrinsic semiconductors are semiconductors in their purest form. An example would be a semiconductor crystal with only silicon atoms.

Extrinsic semiconductors are semiconductors with other atoms mixed in. These other atoms are called impurity atoms. The process of adding impurity atoms is called doping. Doping alters the characteristics of the semiconductor, mainly its conductivity. The impurity atoms have either fewer than four valence electrons or more than four valence electrons. At room temperature (about 25 degree C), an intrinsic semiconductor acts more like an insulator than a conductor. The conductivity of an extrinsic semiconductor is greater than that of an intrinsic semiconductor. The level of conductivity is dependent mainly on the number of impurity atoms that have been added during the doping process.

What Are Diodes Made Out Of?

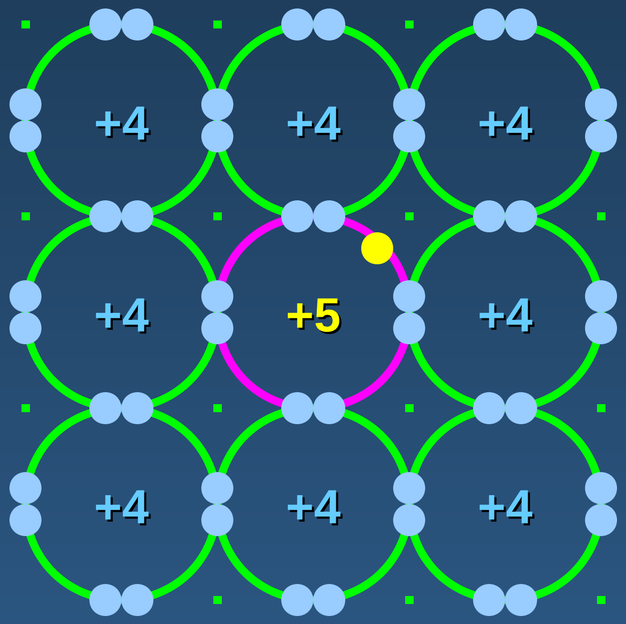
- Silicon (Si) and Germanium (Ge) are the two most common single elements that are used to make Diodes. A compound that is commonly used is Gallium Arsenide (GaAs), especially in the case of LEDs because of it's large bandgap.
- Silicon and Germanium are both group 4 elements, meaning they have 4 valence electrons. Their structure allows them to grow in a shape called the diamond lattice.
- Gallium is a group 3 element while Arsenide is a group 5 element. When put together as a compound, GaAs creates a zincblend lattice structure.
- In both the diamond lattice and zincblend lattice, each atom shares its valence electrons with its four closest neighbors. This sharing of electrons is what ultimately allows diodes to be build. When dopants from groups 3 or 5 (in most cases) are added to Si, Ge or GaAs it changes the properties of the material so we are able to make the P- and N-type materials that become the diode.



The diagram above shows the 2D structure of the Si crystal. The light green lines represent the electronic bonds made when the valence electrons are shared. Each Si atom shares one electron with each of its four closest neighbors so that its valence band will have a full 8 electrons.

N-Type Material

N-Type Material:

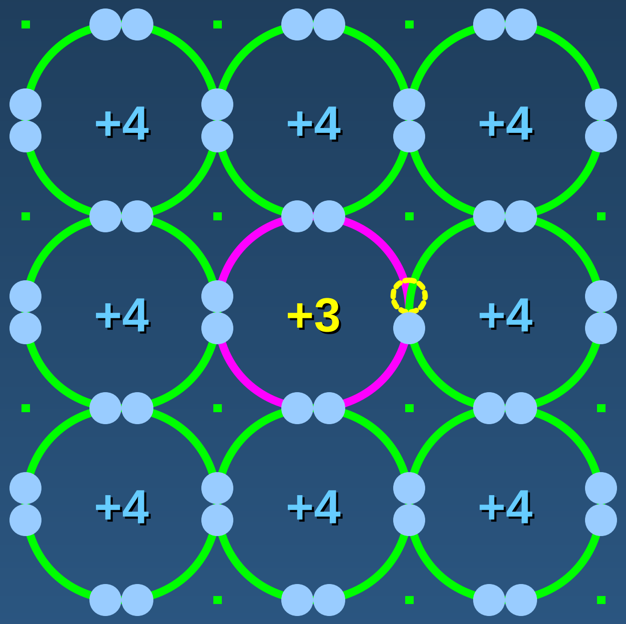


When extra valence electrons are introduced into a material such as silicon an n-type material is produced. The extra valence electrons are introduced by putting impurities or dopants into the silicon. The dopants used to create an n-type material are Group V elements. The most commonly used dopants from Group V are arsenic, antimony and phosphorus.

The 2D diagram to the left shows the extra electron that will be present when a Group V dopant is introduced to a material such as silicon. This extra electron is very mobile.

P-Type Material

P-Type Material:

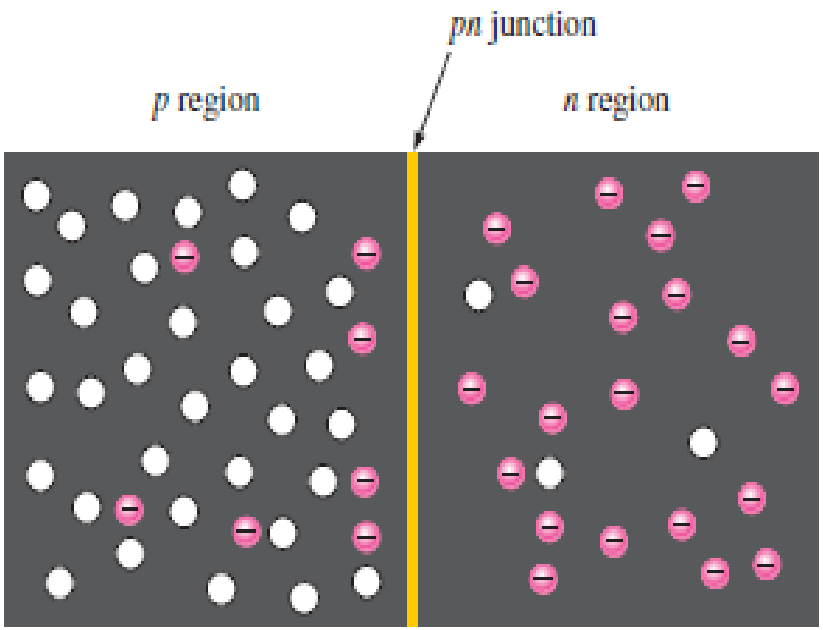


P-type material is produced when the dopant that is introduced is from Group III. Group III elements have only 3 valence electrons and therefore there is an electron missing. This creates a hole (h+), or a positive charge that can move around in the material. Commonly used Group III dopants are aluminum, boron, and gallium.

The 2D diagram to the left shows the hole that will be present when a Group III dopant is introduced to a material such as silicon. This hole is quite mobile in the same way the extra electron is mobile in a n-type material.

PN Junction

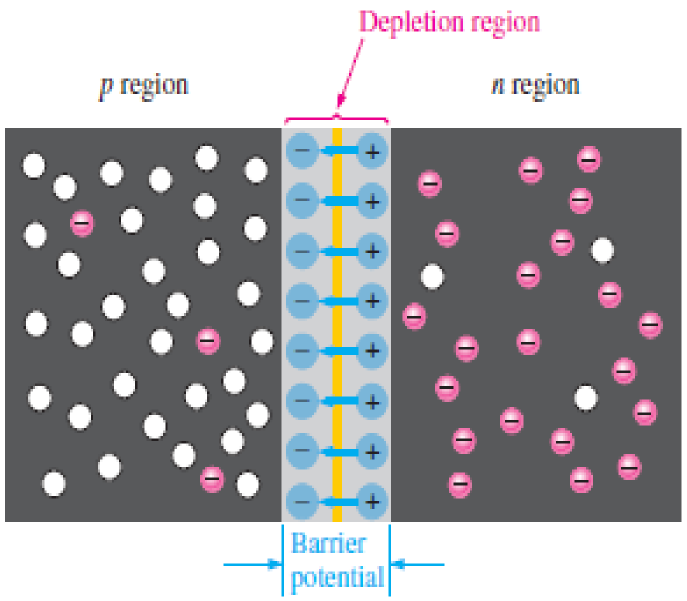
Although P-type material has holes in excess and N-type material has a number of free conduction electron however the net number of proton and electron are equal in each individual material keeping it just neutral.



The basic silicon structure at the instant of junction formation showing only the majority and minority carriers.

Free electrons in the *n region near the pn junction begin to diffuse across the* junction and fall into holes near the junction in the *p region.*

PN Junction

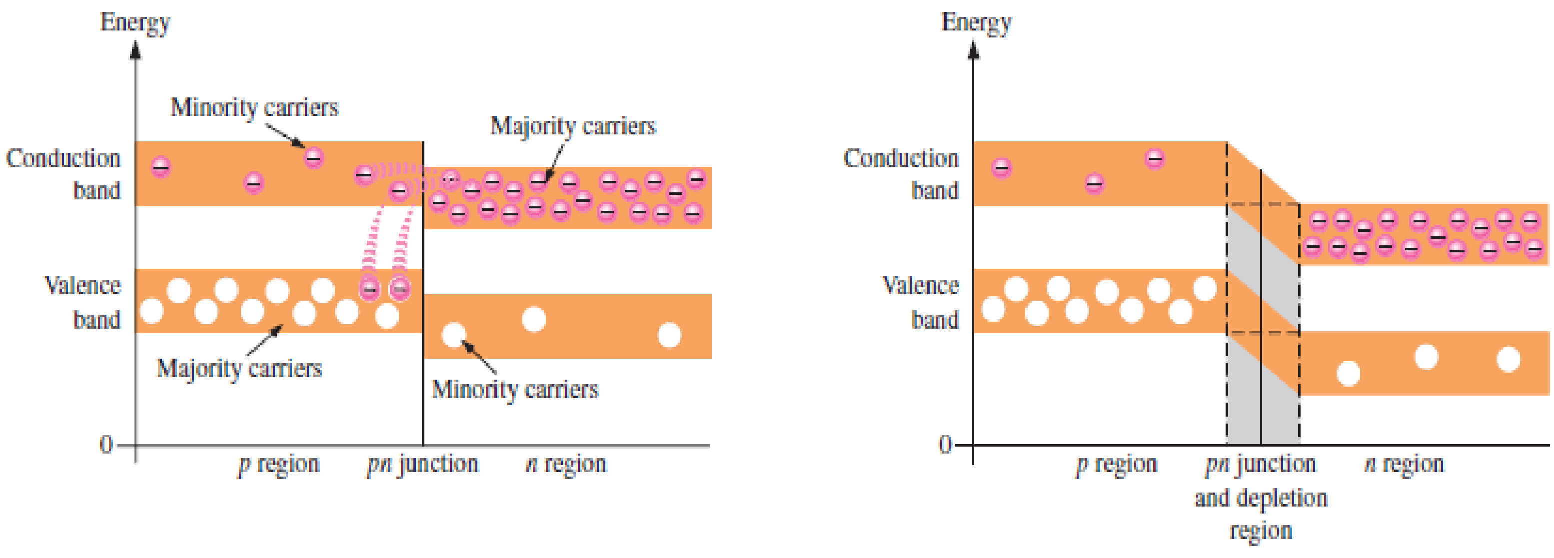


For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n region* and a negative charge is created in the *p region, forming a* barrier potential.

This action continues until the voltage of the barrier repels further diffusion.

The blue arrows between the positive and negative charges in the depletion region represent the electric field.

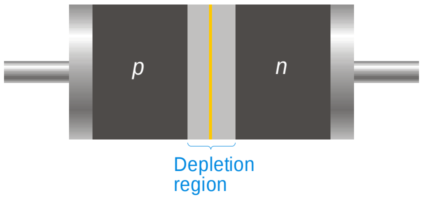
Energy band and potential barrier

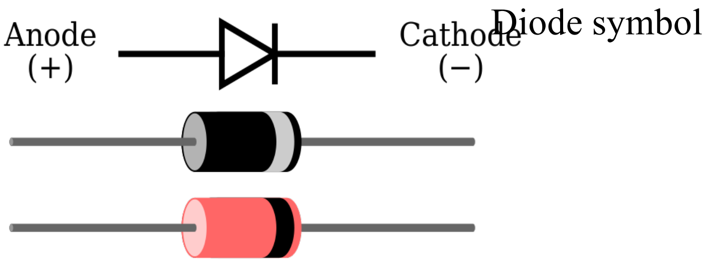


Diodes

- Diode, semiconductor material, such as silicon, in which half is doped as p-region and half is doped as n-region with a pn-junction in between.

- The p region is called **anode** and n type region is called **cathode.**





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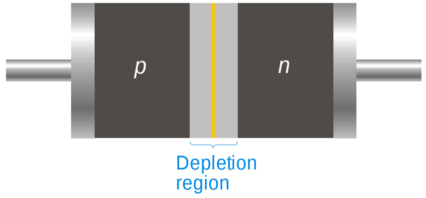
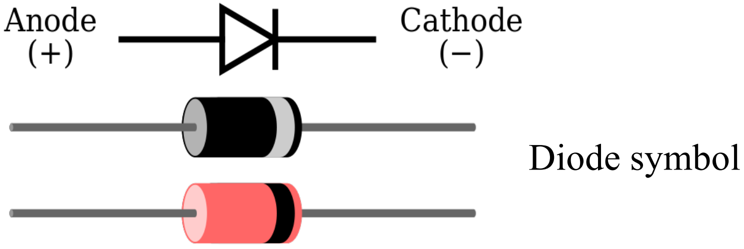
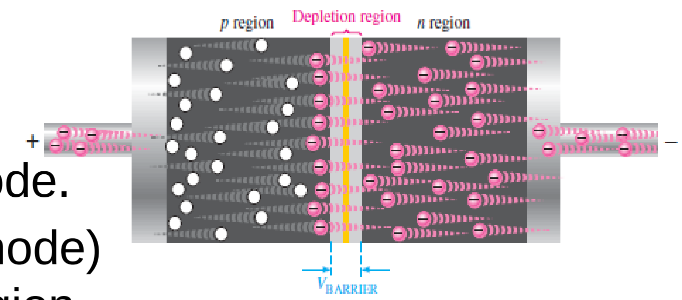




- It conducts current in one direction and offers high (ideally infinite) resistance in other direction.

Forward Biased

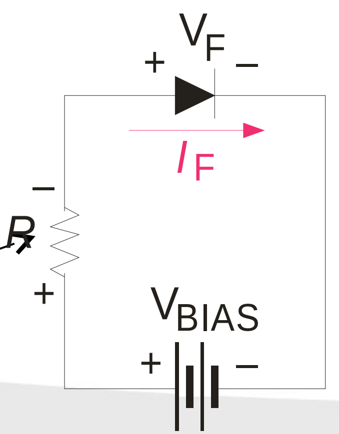
- Forward bias is a condition that allows current through pn junction.
  - A dc voltage (V_{bais}) is applied to bias a diode.
  - Positive side is connected to p-region (anode) and negative side is connected with n-region.
  - V_{bais} must be greater than ‘barrier potential’

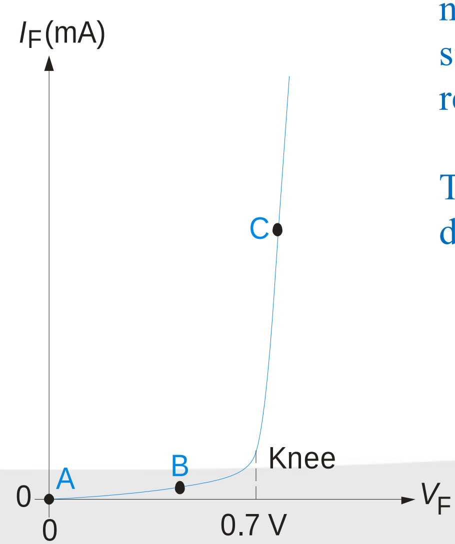


As more electrons flow into the depletion region reducing the number of positive ions and similarly more holes move in reducing the positive ions.

This reduces the width of depletion region.

Current limiting resistance





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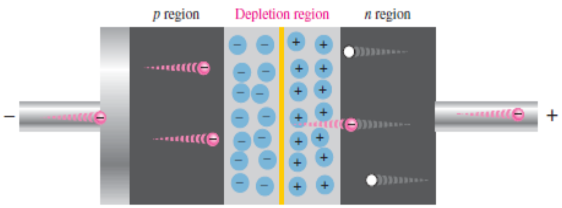
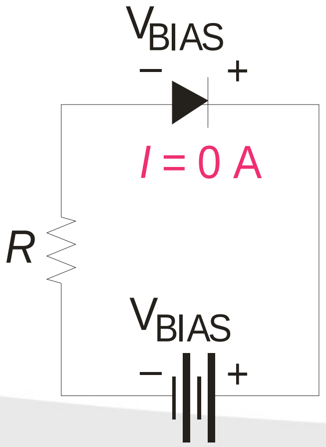
Reverse Biased

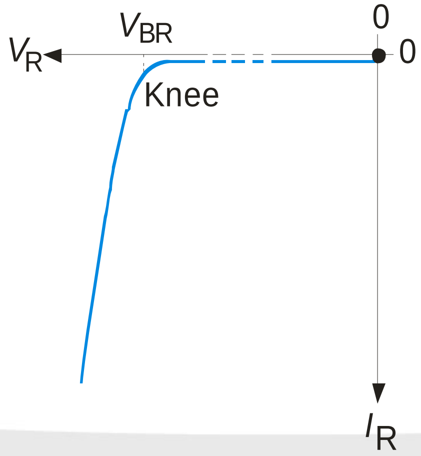
- Reverse bias is a condition that prevents current through junction.
- Positive side of V_{bias} is connected to the n-region whereas the negative side is connected with p-region.
- Depletion region get wider with this configuration.



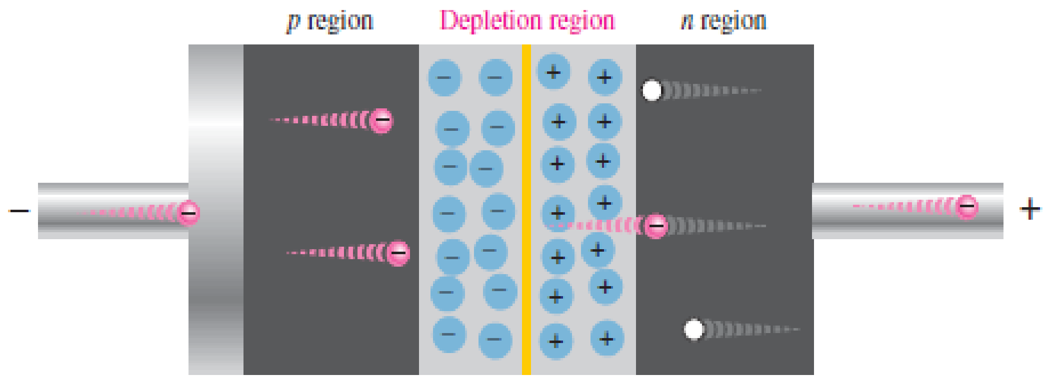
The positive side of bias voltage attracts the majority carriers of n-type creating more positive ions at the junction.

This widens the depletion region.



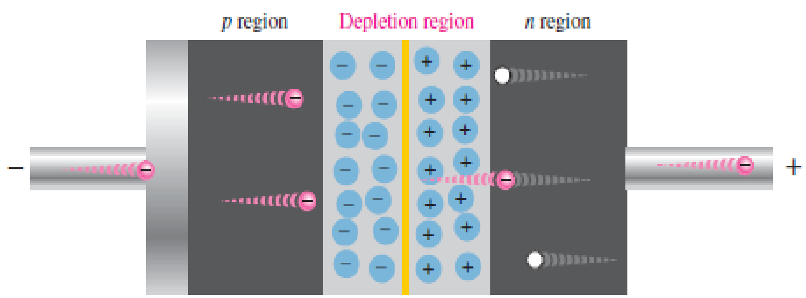


Reverse Current



- A small amount current is generated due to the minority carriers in p and n regions.
- These minority carriers are produced due to thermally generated hole-electron pairs.
- Minority electrons in p-region pushed towards +ve bias voltage, cross junction and then fall in the holes in n-region and still travel in valance band generating a hole current.

Reverse Breakdown



- If the external bias voltage is increased to a value call *breakdown voltage* the reverse current can increase drastically.
- Free minority electrons get enough energy to knock valance electron into the conduction band.
- The newly released electron can further strike with other atoms.
- The process is called ***avalanche effect.***

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Breakdown Voltage

In reverse bias the current that flows prior to breakdown is mainly the result of thermally produced minority current carriers. This current is called leakage current and is usually designated I_R . Leakage current increases mainly with temperature and is relatively independent of changes in reverse-bias voltage.

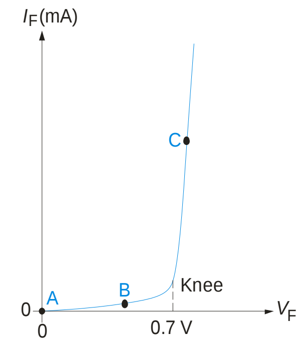
Avalanche occurs when the reverse-bias voltage, V_R , becomes excessive. Thermally produced free electrons on the P side are accelerated by the voltage source to very high speeds as they move through the diode. These electrons collide with valence electrons in other orbits. These valence electrons are also set free and accelerated to very high speeds, thereby dislodging even more valence electrons. The process is cumulative; hence, we have an avalanche effect.

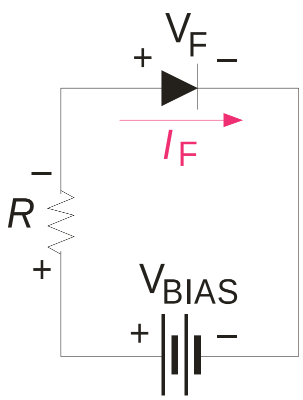
When the breakdown voltage, V_{BR} , is reached, the reverse current, I_R , increases sharply. Diodes should not be operated in the breakdown region. Most rectifier diodes have breakdown voltages exceeding 50 V.

Diode V-I Characteristic

VI Characteristic for forward bias.

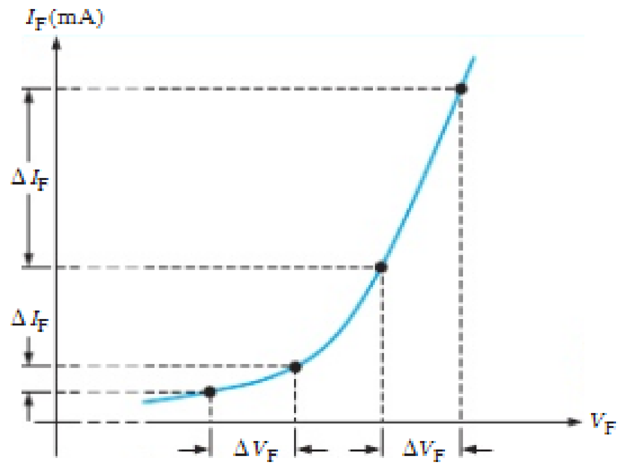
- The current in forward biased called *forward current* and is designated I_f.
- At 0V (V_{bias}) across the diode, there is no forward current.
- With gradual increase of V_{bias}, the forward voltage and forward current increases.
- A resistor in series will limit the forward current in order to protect the diode from overheating and permanent damage.
- A portion of forward-bias voltage drops across the limiting resistor.
- Continuing increase of V_f causes rapid increase of forward current but only a gradual increase in voltage across diode.





Diode V-I Characteristic

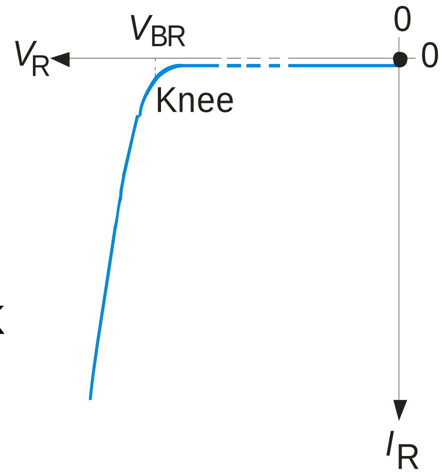
- **Dynamic Resistance:**
- The resistance of diode is not constant but it changes over the entire curve. So it is called dynamic resistance.



The dynamic resistance r'_d decreases as you move up the curve, as indicated by the decrease in the value of $\Delta V_F / \Delta I_F$.

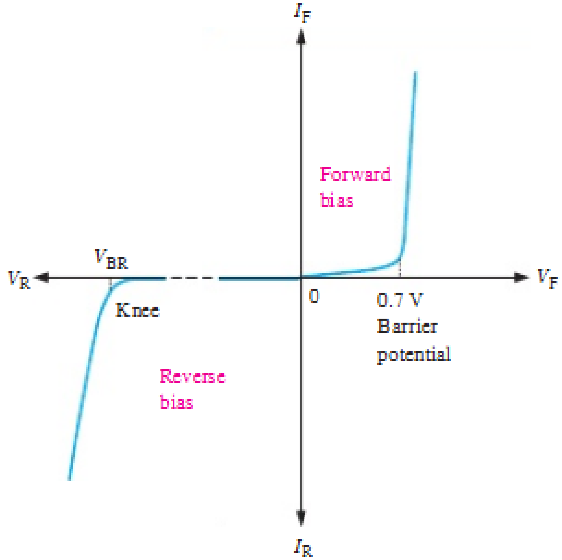
Diode V-I Characteristic

- **VI Characteristic for reverse bias.**
  - With 0V reverse voltage there is no reverse current.
  - There is only a small current through the junction as the reverse voltage increases.
  - At a point, reverse current shoots up with the break down of diode. The voltage called break down voltage. This is not normal mode of operation.
  - After this point the reverse voltage remains at approximately V_{BR} but I_R increase very rapidly.
  - Break down voltage depends on doping level, set by manufacturer.



Diode V-I Characteristic

- The complete V-I characteristic curve



The complete *V-I* characteristic curve for a diode.

Zener Diodes

- A Zener diode is a silicon pn junction that is designed for operation in reverse-breakdown region
- When a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically, and this is key to the Zener diode operation.
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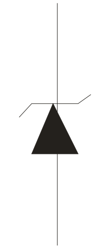
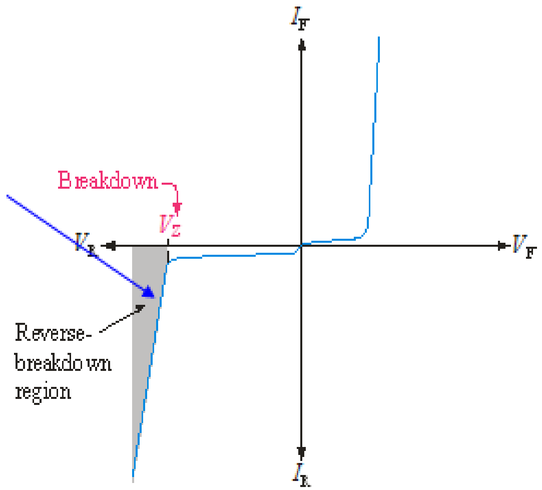
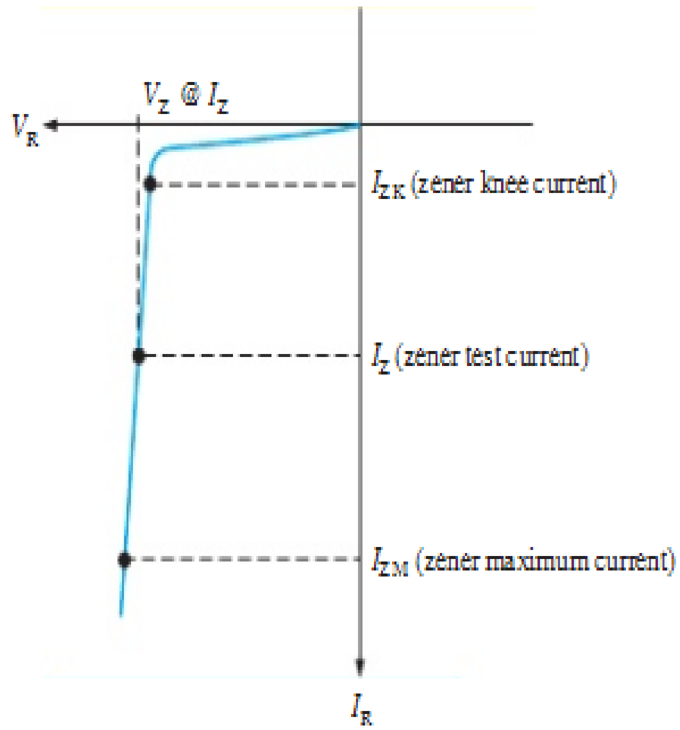




Characteristic curve

Zener Breakdown Characteristic

- As the reverse voltage (V_R) increases, the reverse current(I_R) remains extremely small up to the knee of the curve.
- Reverse current is also called Zener current(I_Z).
- At knee point the breakdown effect begins, the internal Zener resistance (Z_Z) begins to decrease.
- The reverse current increase rapidly.
- The Zener breakdown (V_Z) voltage remains nearly constant.



Reverse characteristic of a zener diode. V_Z is usually specified at a value of the zener current known as the test current.

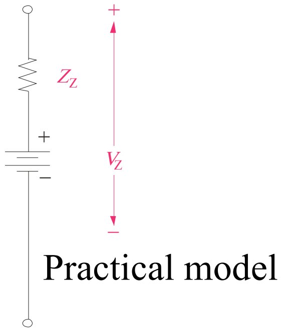
Zener Diode Impedence

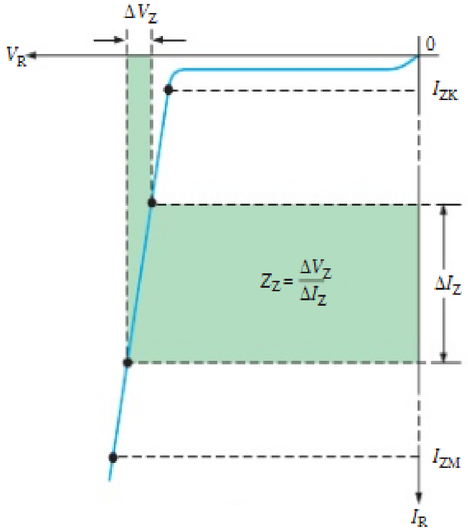
- The zener impedance, Z_Z, is the ratio of a change in voltage in the breakdown region to the corresponding change in current:

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

What is the zener impedance if the zener diode voltage changes from 4.79 V to 4.94 V when the current changes from 5.00 mA to 10.0 mA?

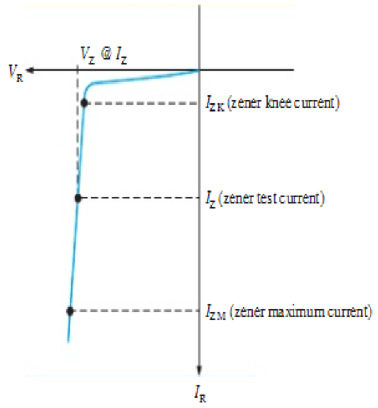
$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} = \frac{0.15\ \text{V}}{5.0\ \text{mA}} = 30\ \Omega$$





Zener Regulation

- The ability to keep the reverse voltage constant across its terminal is the key feature of the Zener diode.
- It maintains constant voltage over a range of reverse current values.
- A minimum reverse current I_{ZK} must be maintained in order to keep diode in regulation mode. Voltage decreases drastically if the current is reduced below the knee of the curve.
- Above I_{ZM}, max current, the Zener may get damaged permanently.



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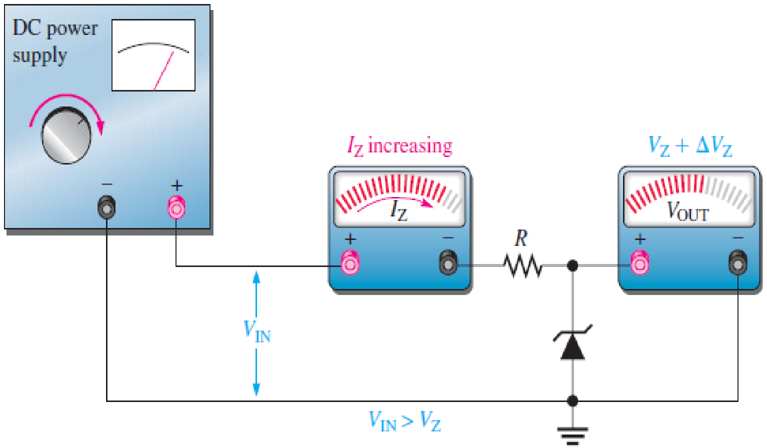
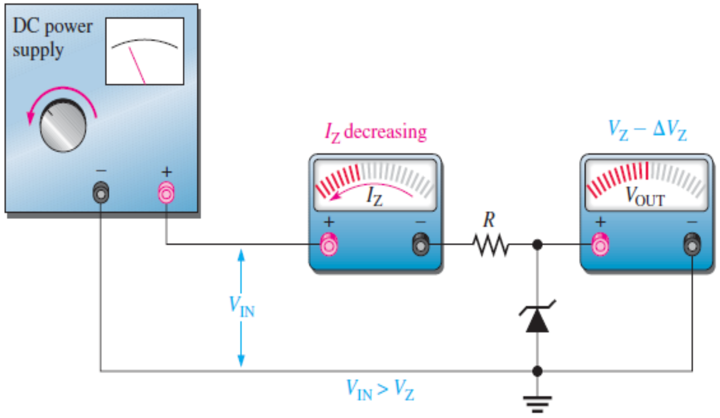
Zener Regulation

- Zener Regulation with variable input voltage:



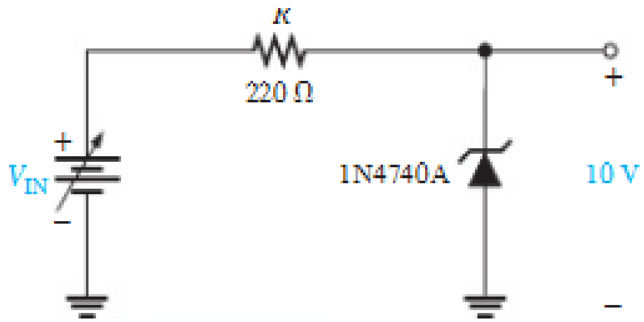


As the input voltage changes, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).

Zener Regulation

- Zener Regulation with variable input voltage

  - Ideal model of IN4047A
  - I_{ZK} = 0.25mA
  - V_Z = 10V
  - $P_{D(max)}$ = 1W



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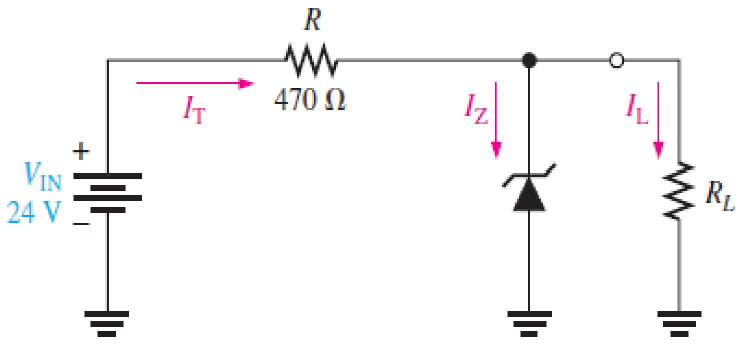
Zener Regulation

- Zener Regulation with variable load



It maintains voltage a nearly constant across RL as long as Zener current is within I_{ZK} and I_{ZM}.

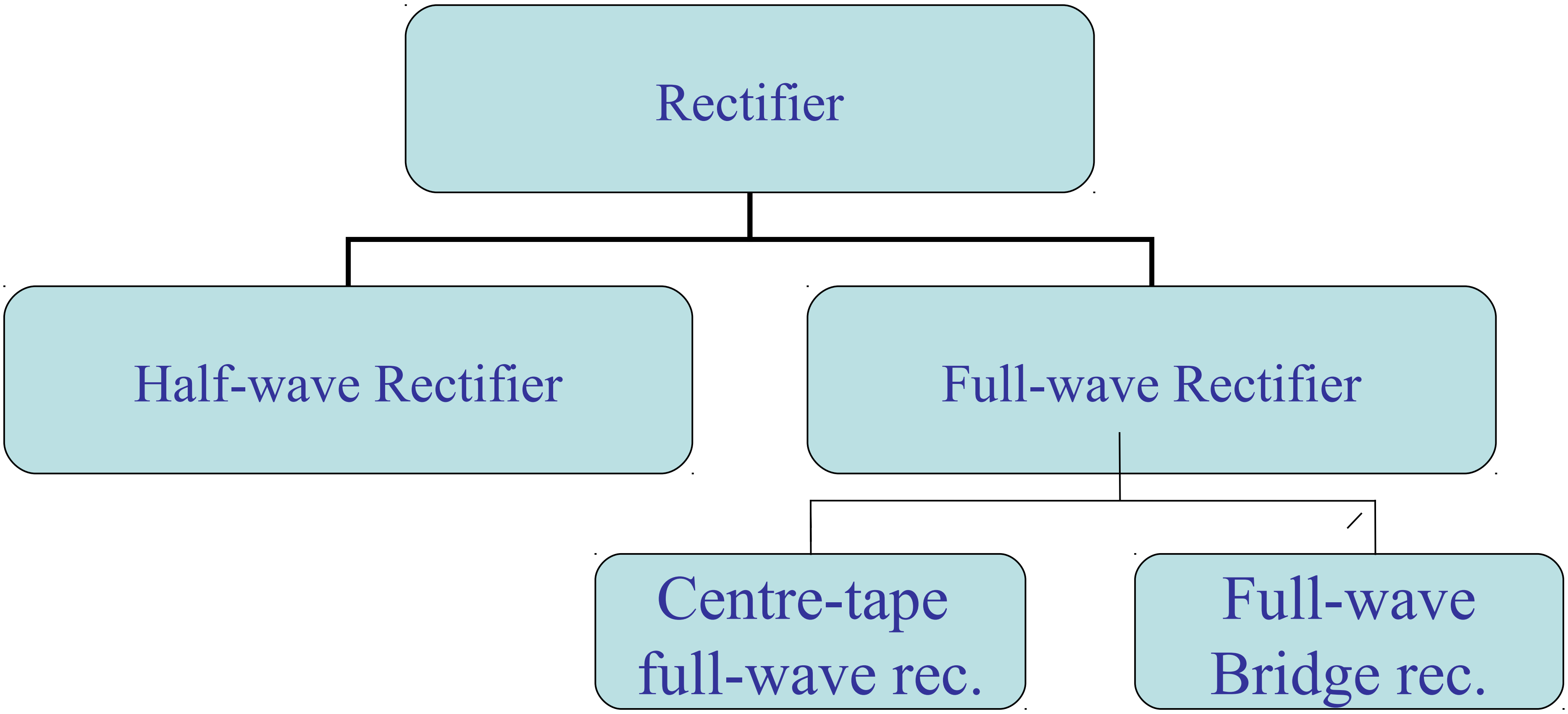
$$V_Z = 12\text{ V},$$
$$I_{ZK} = 1\text{ mA},$$
$$I_{ZM} = 50\text{ mA}.$$

RECTIFIERS

Most electronic equipment requires dc voltages to operate properly. Since most equipment is connected to the 220-Vac power line, this ac voltage must somehow be converted to the required dc value. A circuit that converts the ac power-line voltage to the required dc value is called a power supply. The most important components in power supplies are rectifier diodes , which convert ac line voltage to dc voltage. Diodes are able to produce a dc output voltage because they are unidirectional devices allowing current to flow through them in only one direction.

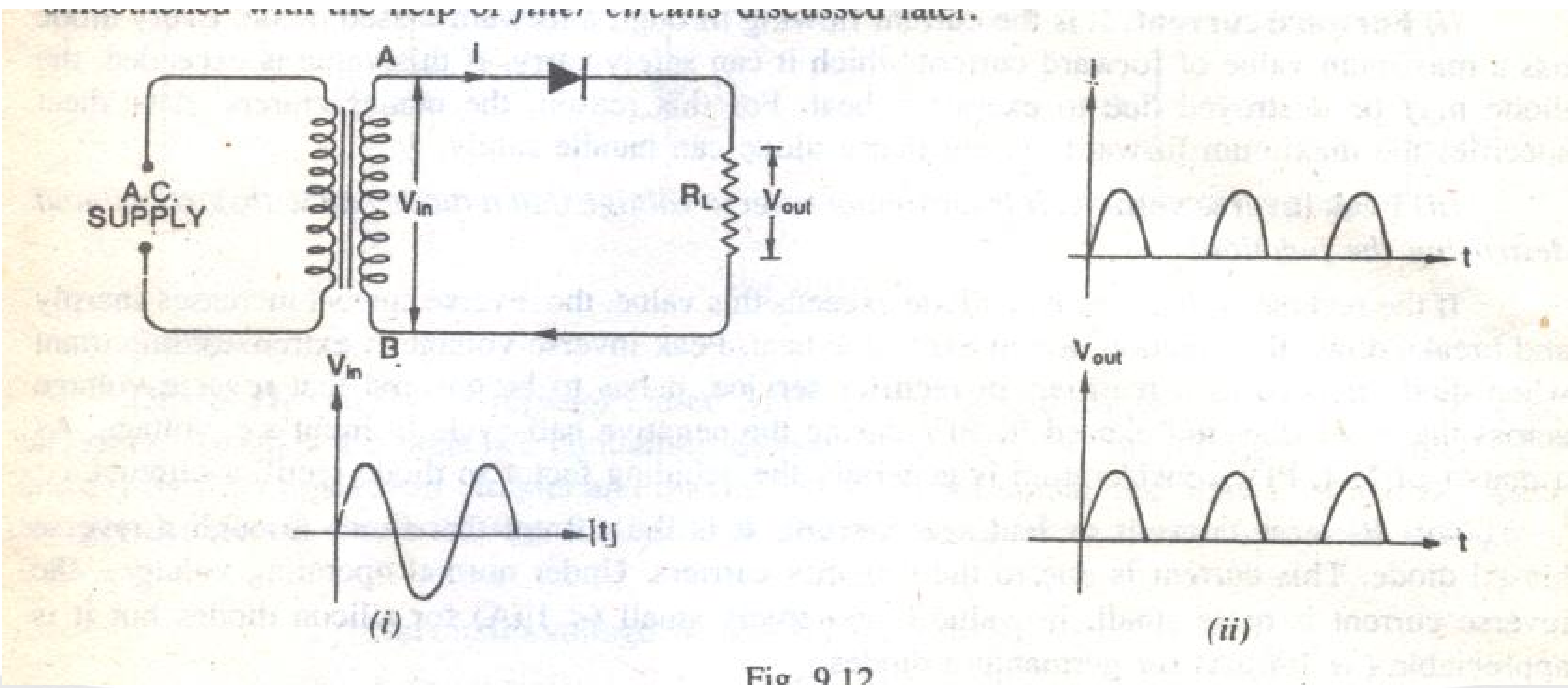
A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which is in only one direction, a process known as rectification.

TYPES OF RECTIFIERS



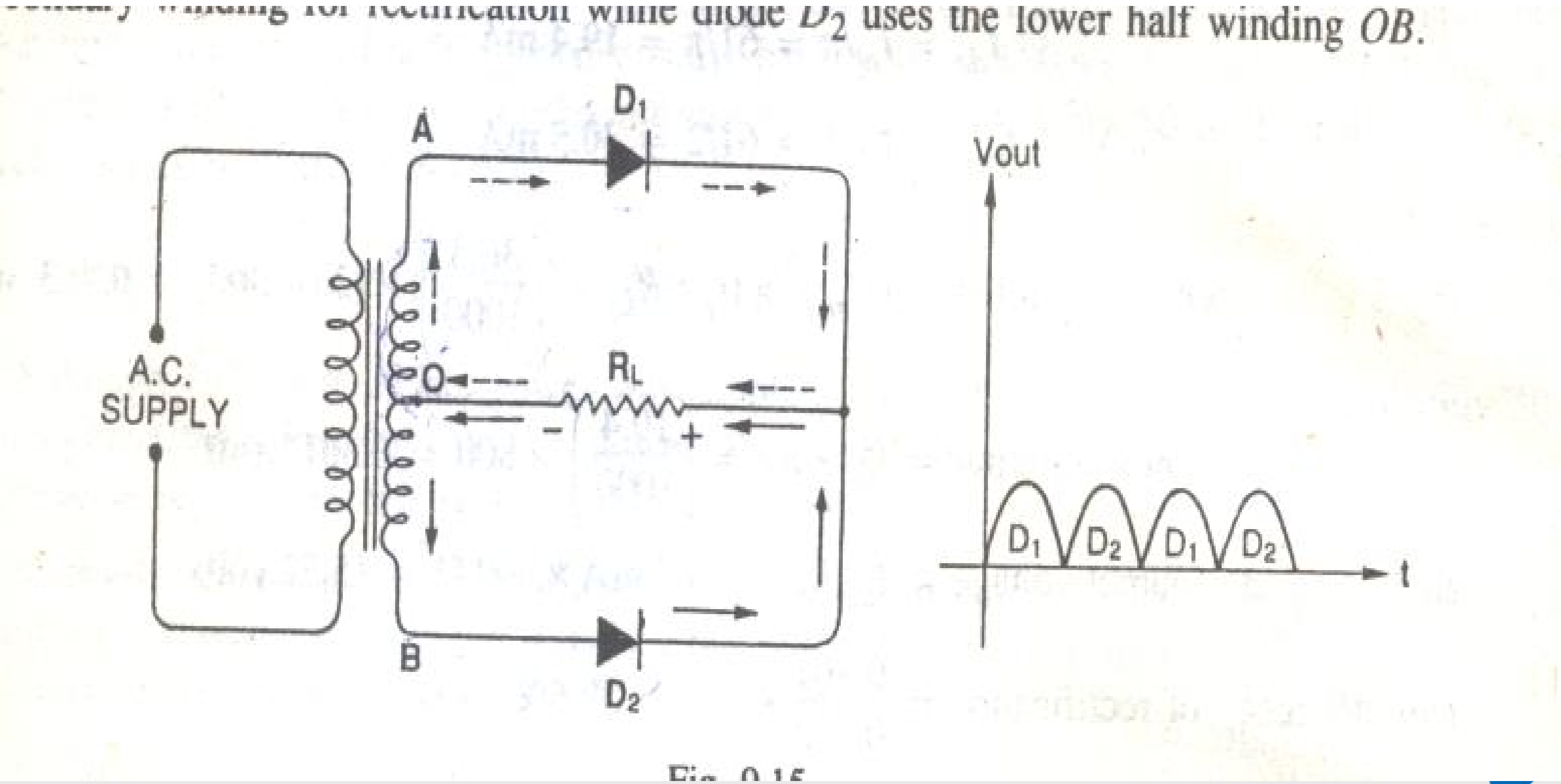
HALF WAVE RECTIFIER

- Circuit Diagram with waveforms:



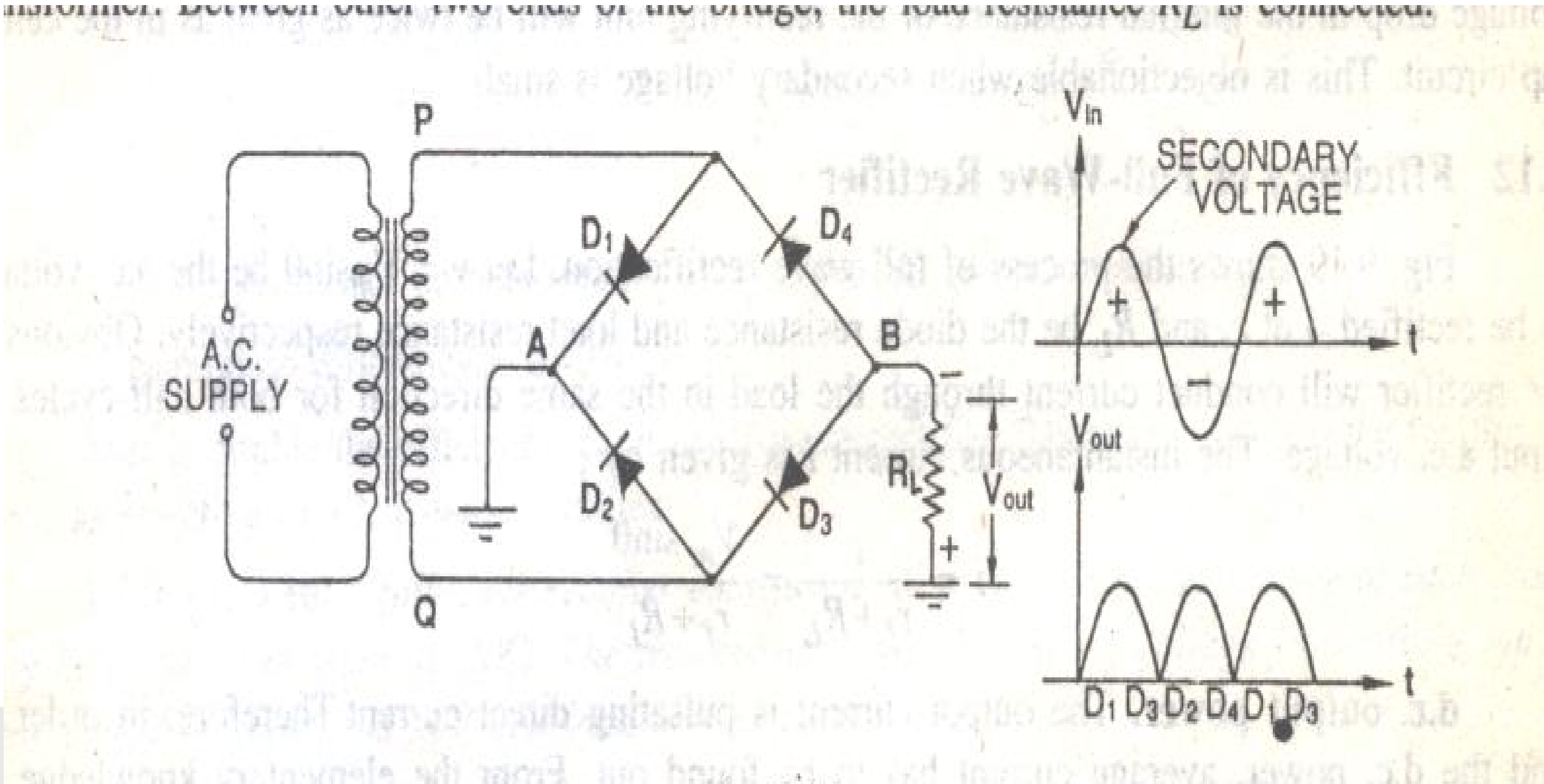
FULL WAVE RECTIFIER

- Centre-tape full-wave Rectifier:
- Circuit Diagram with waveforms:



FULL WAVE RECTIFIER

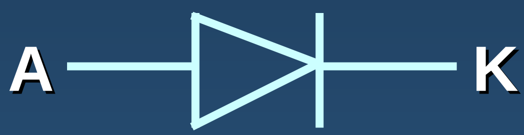
- Full-wave bridge Rectifier:
- Circuit Diagram with waveforms:



Types of Diodes and Their Uses

PN Junction Diodes:

Are used to allow current to flow in one direction while blocking current flow in the opposite direction. The pn junction diode is the typical diode that has been used in the previous circuits.

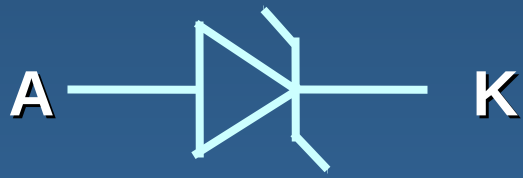


Schematic Symbol for a PN Junction Diode

Representative Structure for a PN Junction Diode

Zener Diodes:

Are specifically designed to operate under reverse breakdown conditions. These diodes have a very accurate and specific reverse breakdown voltage.

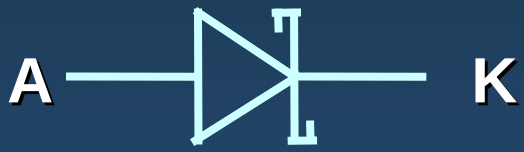


Schematic Symbol for a Zener Diode

Types of Diodes and Their Uses

Schottky Diodes:

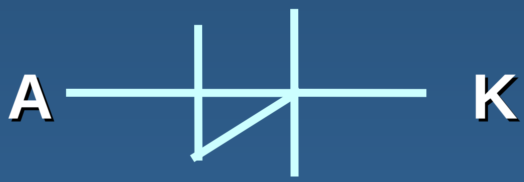
These diodes are designed to have a very fast switching time which makes them a great diode for digital circuit applications. They are very common in computers because of their ability to be switched on and off so quickly.



Schematic Symbol for a Schottky Diode

Shockley Diodes:

The Shockley diode is a four-layer diode while other diodes are normally made with only two layers. These types of diodes are generally used to control the average power delivered to a load.



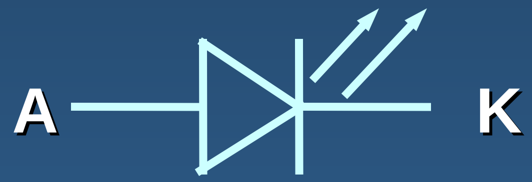
Schematic Symbol for a four-layer Shockley Diode

Kristin Ackerson, Virginia Tech EE
Spring 2002

Types of Diodes and Their Uses

Light-Emitting Diodes:

Light-emitting diodes are designed with a very large bandgap so movement of carriers across their depletion region emits photons of light energy. Lower bandgap LEDs (Light-Emitting Diodes) emit infrared radiation, while LEDs with higher bandgap energy emit visible light. Many stop lights are now starting to use LEDs because they are extremely bright and last longer than regular bulbs for a relatively low cost.

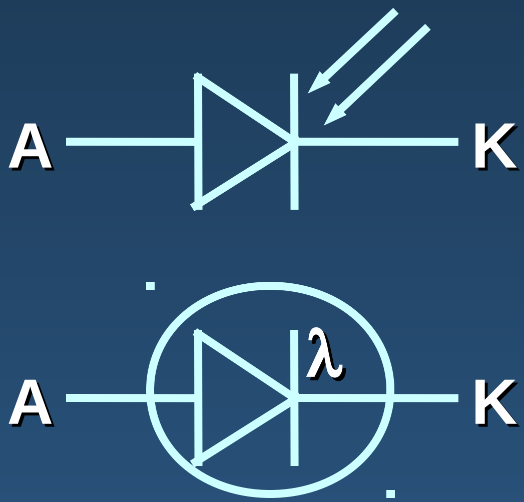


Schematic Symbol for a Light-Emitting Diode

The arrows in the LED representation indicate emitted light.

Types of Diodes and Their Uses

Photodiodes:



Schematic Symbols for Photodiodes

While LEDs emit light, Photodiodes are sensitive to received light. They are constructed so their pn junction can be exposed to the outside through a clear window or lens.

In Photoconductive mode the saturation current increases in proportion to the intensity of the received light. This type of diode is used in CD players.

In Photovoltaic mode, when the pn junction is exposed to a certain wavelength of light, the diode generates voltage and can be used as an energy source. This type of diode is used in the production of solar power.