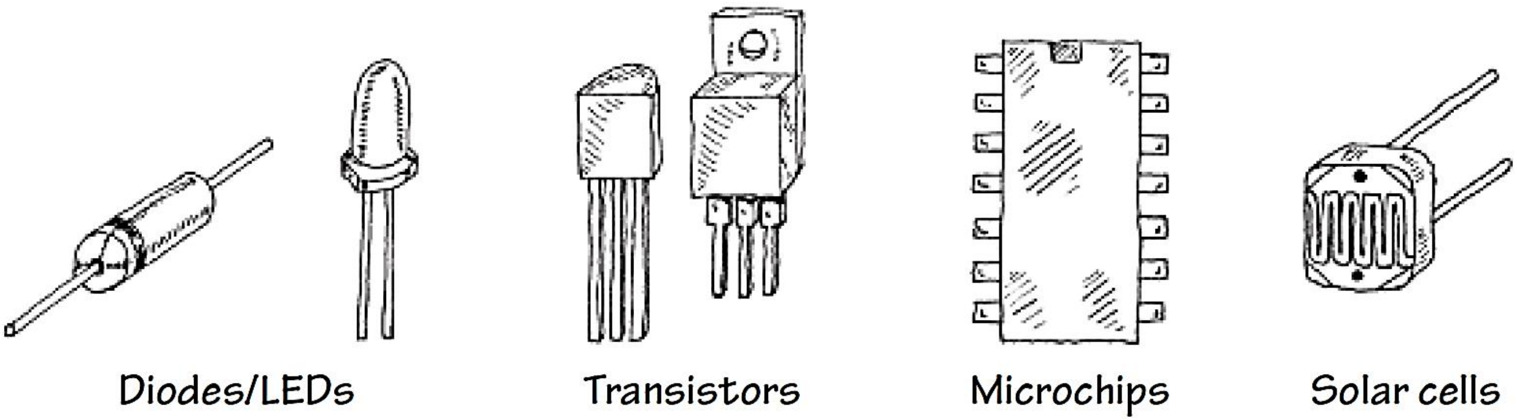
Ch7: Diodes

Semiconductor Physics

Semiconductors

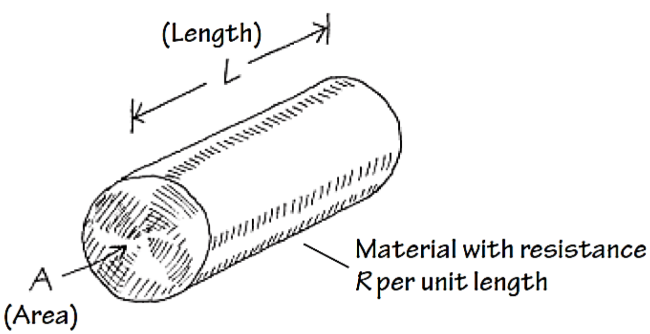
Semiconductors are used extensively in electronic circuits today. Electronic devices, such as **diodes**, **transistors**, **thyristors**, **thermistors**, **photovoltaic cells**, **phototransistors**, **photoresistors**, **lasers**, and **integrated circuits** (ICs), are all made from semiconductive materials, or semiconductors.



Semiconductors

Materials classification by their **ability to conduct electricity**:

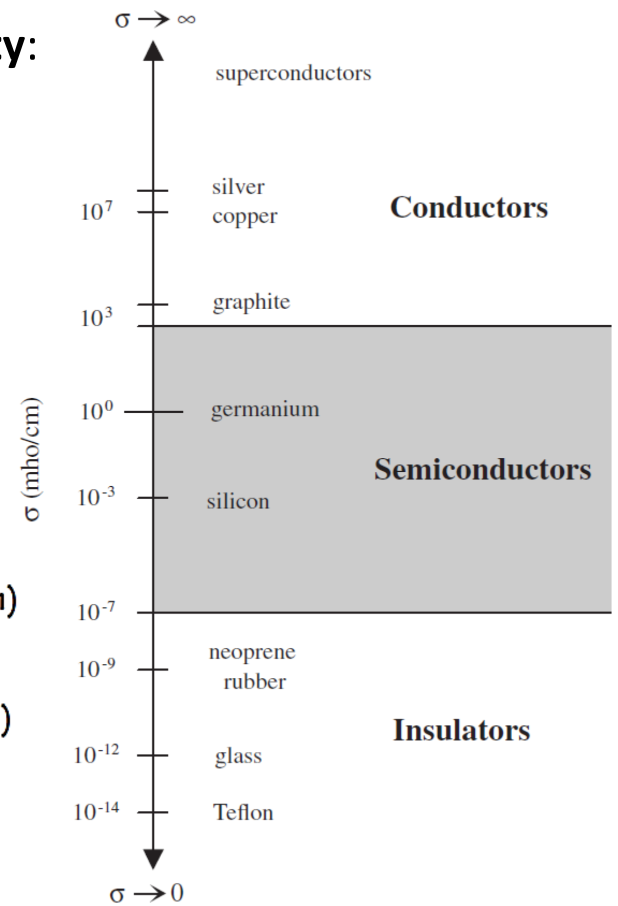
- **Conductors** that easily pass an electric current, such as silver and copper.
- **Insulators** that do not pass an electric current, such as rubber, wood, and glass.
- **Semiconductor** whose conductivity lies between those of conductors and insulators, such as silicon and germanium.



$$\rho = R\frac{A}{L} \quad \text{(Resistivity ohm·cm)}$$

$$\sigma = \frac{1}{\rho} \quad \text{(Conductivity mho/cm)}$$

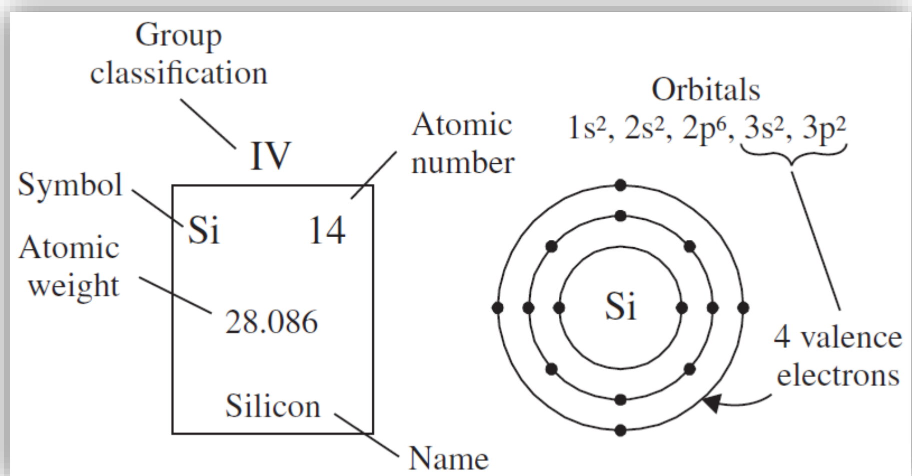
$$\text{mho} = \frac{1}{\text{ohm}} = \frac{1}{\Omega} = \mho$$

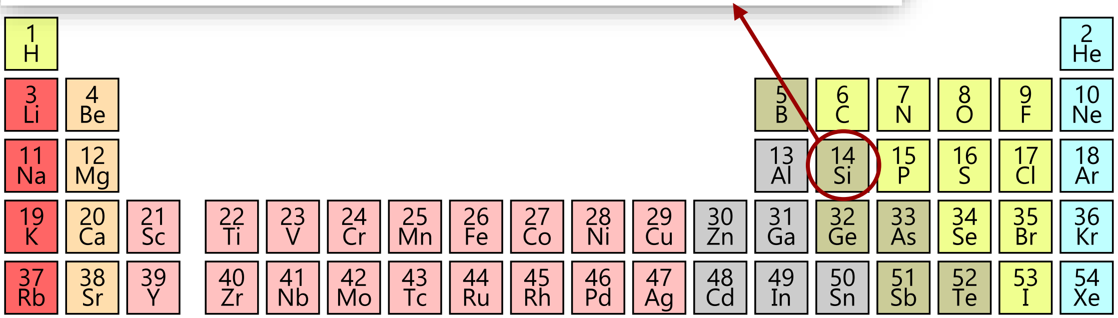


There are two types of **semiconductors** based on their structure: **Intrinsic** and **Extrinsic**.

Intrinsic Semiconductors

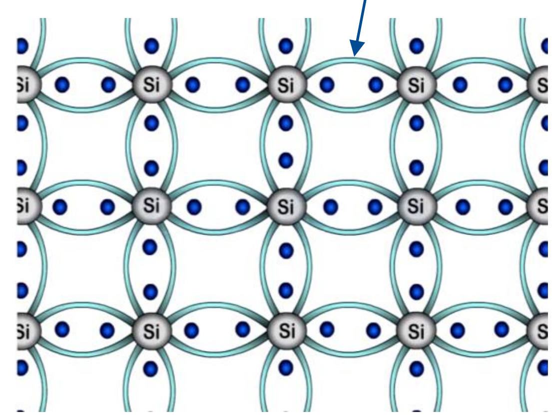
Intrinsic Semiconductors are **Pure** form of semiconductors like **Silicon** (**Si**) which is the most important semiconductor used in building electrical devices. In pure form, conductivity of silicon depends on **temperature**.





4 valence electrons orbiting in its outermost shell. The atom needs a total of **8** electron in its outer shell to become **stable**. So, silicon atoms are bonded together and form the structure.

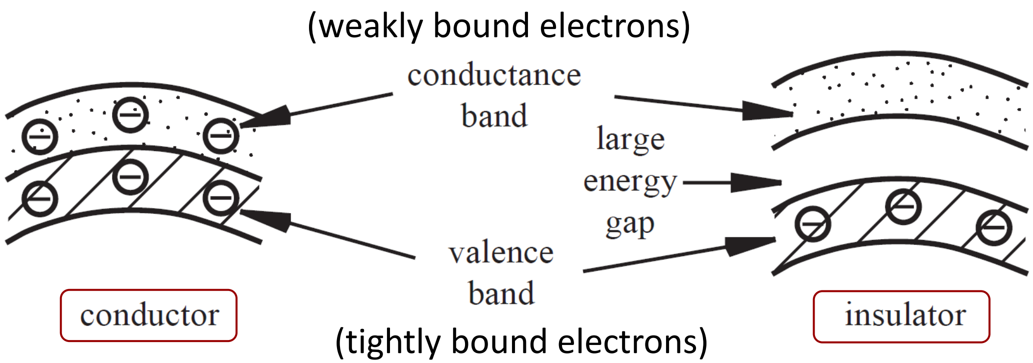
Covalent Bond

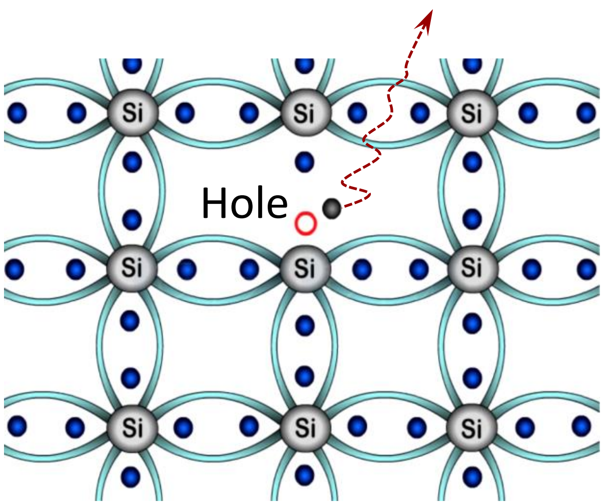


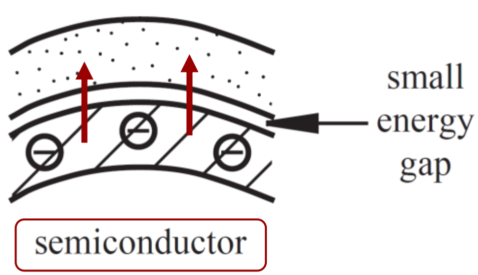
(no free electron)

Intrinsic Semiconductors

By increasing **temperature**, some of the valence electrons absorb energy, break the bonds, freely move, and easily jump to the conductance band to produce a current. **Absence** of these electrons in the valence band is called **hole**.



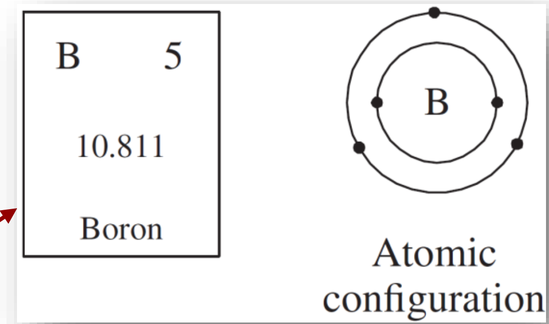


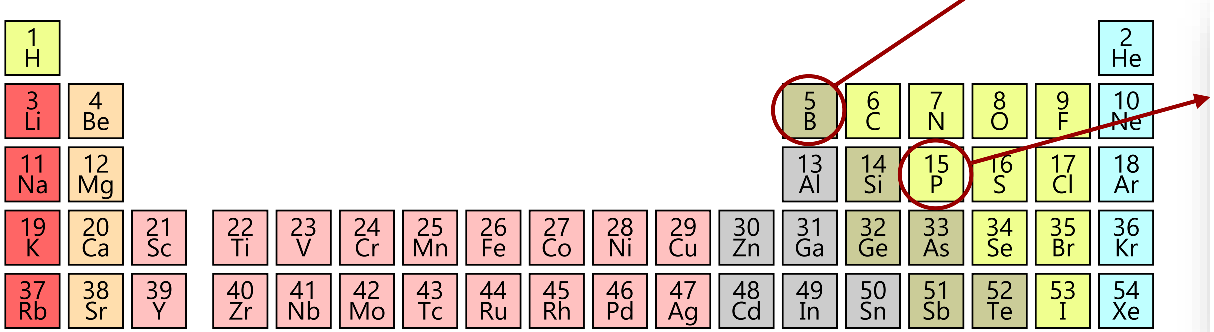


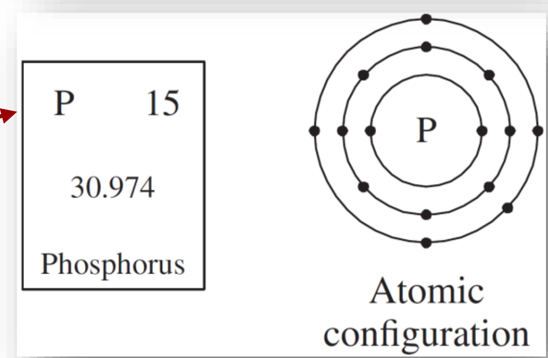
Extrinsic Semiconductors

Intrinsic semiconductors act more as an insulator than a conductor (since they do not have free electros), and they do not have the ability to change conductive states when an external voltage is applied. Hence, **impurities** should be added to intrinsic semiconductors **to improve conductivity** and make **Extrinsic Semiconductors**. This process is called **Doping**.

Many ingredients can be added in the doping process. Two of the most important ingredients that can alter the electrical conductivity dramatically are **Phosphorus** (**P**) and **Boron** (**B**).

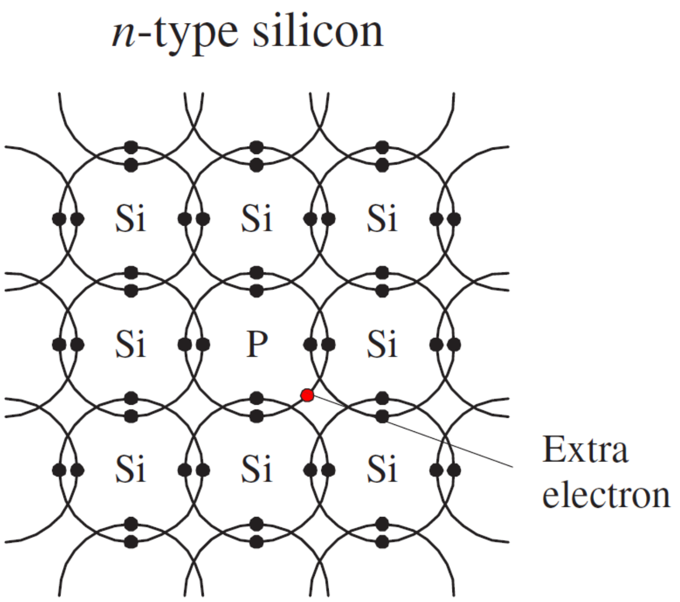




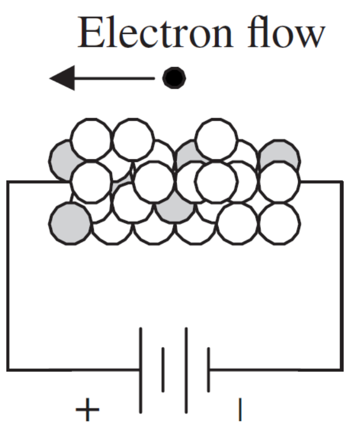


Extrinsic Semiconductors (n-Type)

Phosphorus (**P**) has five valence electrons. Four of its valence electrons will form covalent bonds with the valence electrons of four neighboring silicon atoms and the fifth valence electron will be loosely floating about the atoms.



If a voltage is applied across the silicon-phosphorus mixture, the **unbound electron** will migrate through the doped silicon **toward the positive voltage end**.

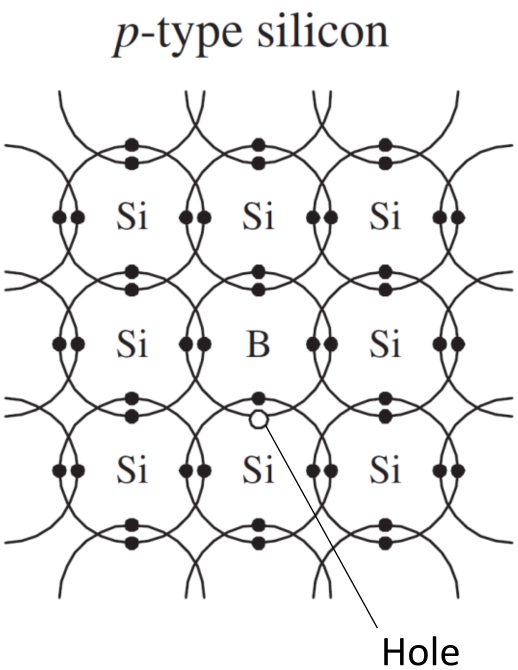


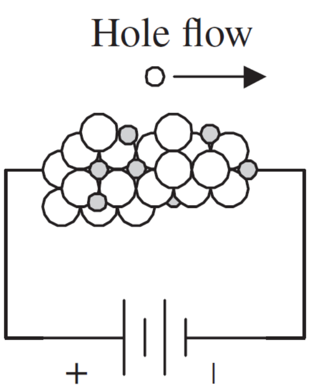
Silicon that is doped with phosphorus is referred to as **n-type silicon**, or **negative-charge-carrier-type** silicon.

Extrinsic Semiconductors (p-Type)

Boron (**B**) has three valence electrons. All three of its valence electrons will form covalent bonds with the valence electrons of neighboring silicon atoms and there will be a vacant spot (called a **hole**) within the covalent bond between one boron and one silicon atom.

If a voltage is applied across the silicon-boron mixture, the **hole** (which acts like a **positive charge**!) will move toward the **negative voltage end**, while a neighboring electron will fill in its place (**consequently, electrons flow**).

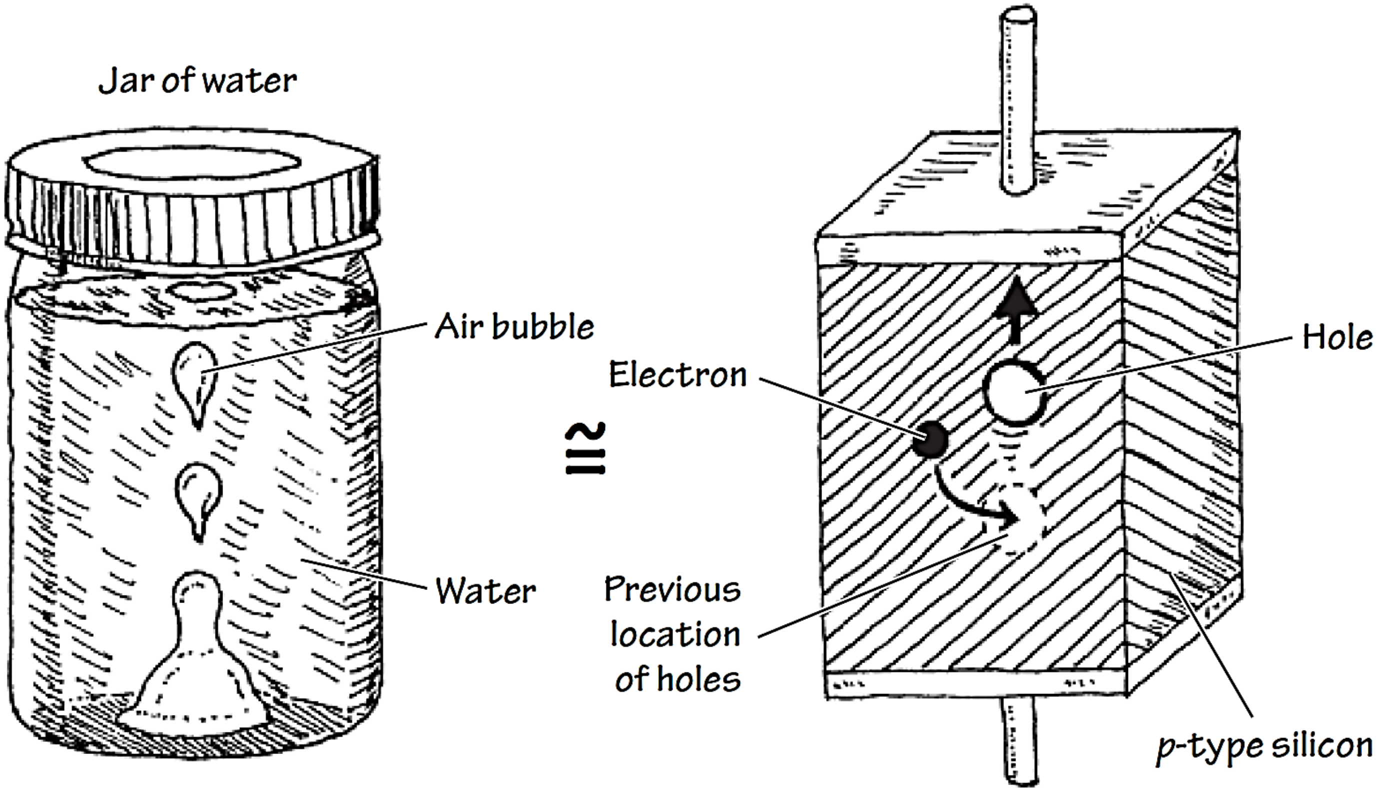




Silicon that is doped with boron is referred to as **p-type silicon**, or **positive-charge-carrier-type** silicon.

How Can Holes Move?

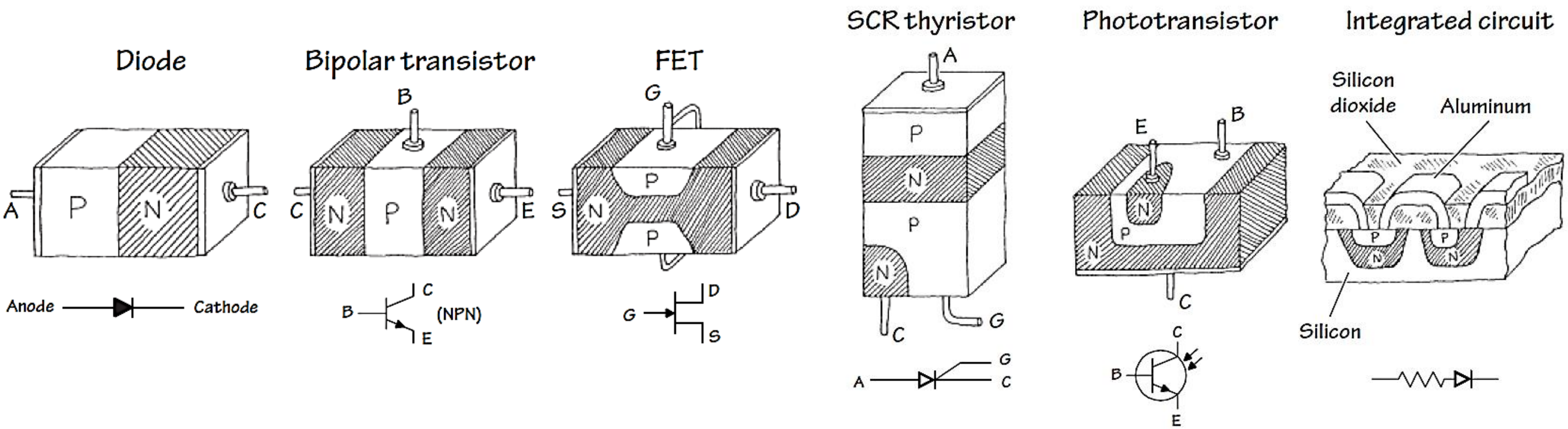
Turn a sealed bottle of water upside down and then right side up. The bubble trapped in the bottle will move in the opposite direction of the water!



Applications

We now have two new conductors with two unique ways of passing an electric current, one does it with **extra unbound electrons** (**n-type silicon**), the other does it with **holes** (**p-type silicon**).

The **interaction** between n-type and p-type semiconductor materials in different configurations/combinations is the basis for most semiconductor electronic devices.

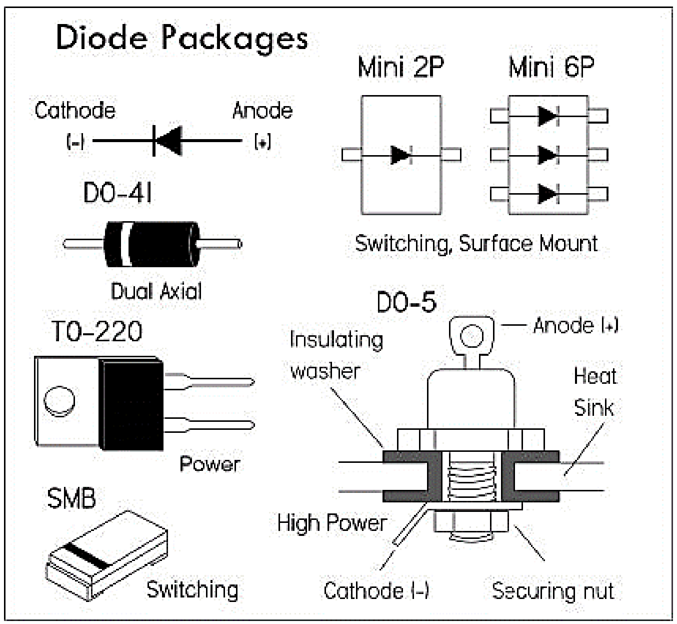


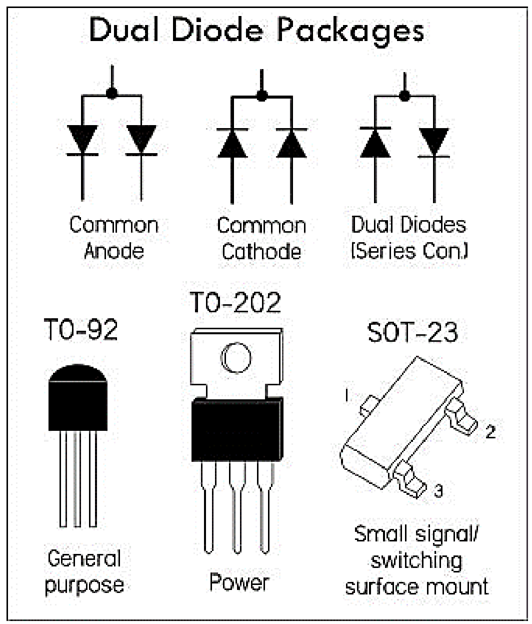
Diodes

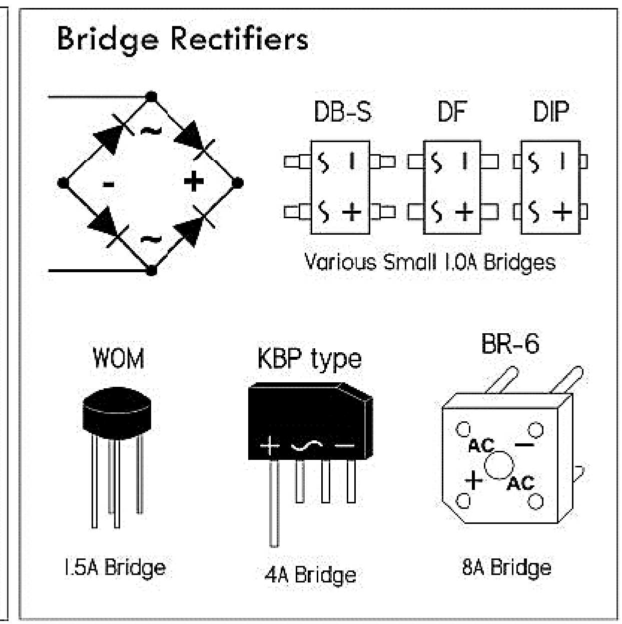
Diode

Diode is a two-lead (anode and cathode) semiconductor device that acts as a **one-way** gate to electric current flow.

- When a diode's anode lead is made more positive in voltage than its cathode lead (***forward biasing***) current is permitted to flow through the device.
- When polarities are reversed (***reversed biasing***) the diode acts to block current flow.

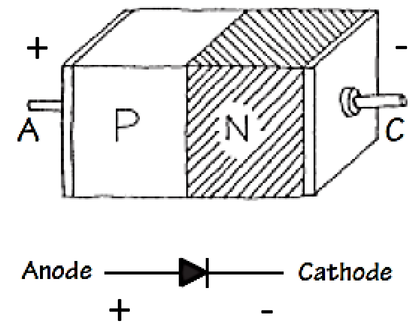




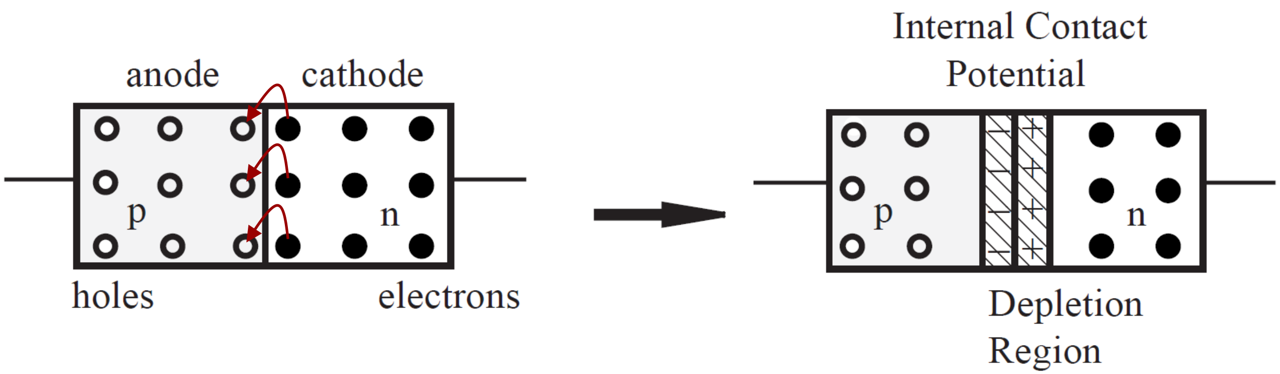


p-n Junction Diode

A **p-n Junction Diode** (**Rectifier Diode**) is formed by sandwiching together n-type and p-type silicon. The **n-type** side is the **cathode end** (-), and the **p-type** side is the **anode end** (+).

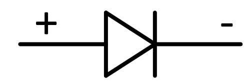


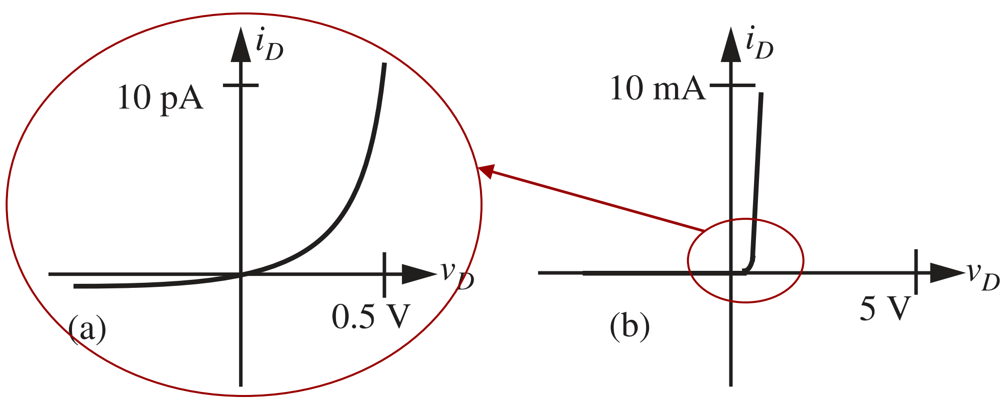
At the p-n junction, electrons from the n-type silicon can diffuse to occupy the holes in the p-type silicon, creating what is called a **Depletion Region**. A **small electric field** develops across this thin depletion region due to the diffusion of electrons. This results in a voltage difference across the depletion region called the **Contact Potential**. For silicon, the contact potential is on the order of 0.6-0.7 V.

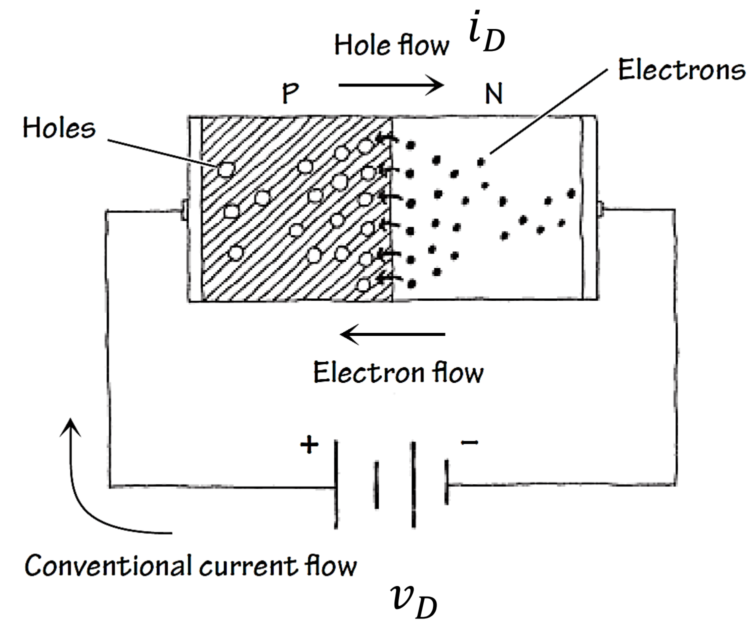


Forward-Biased

When a diode is connected to a **voltage source** as shown, electrons from the n-type side and holes from the p-type side are forced toward the center (p-n interface). As the applied voltage approaches the value of the contact potential (0.6-0.7 V for silicon, 0.2-0.3 V for germanium), the **depletion region shrinks**, the electrons and holes combine, and the **current flow increases exponentially**.





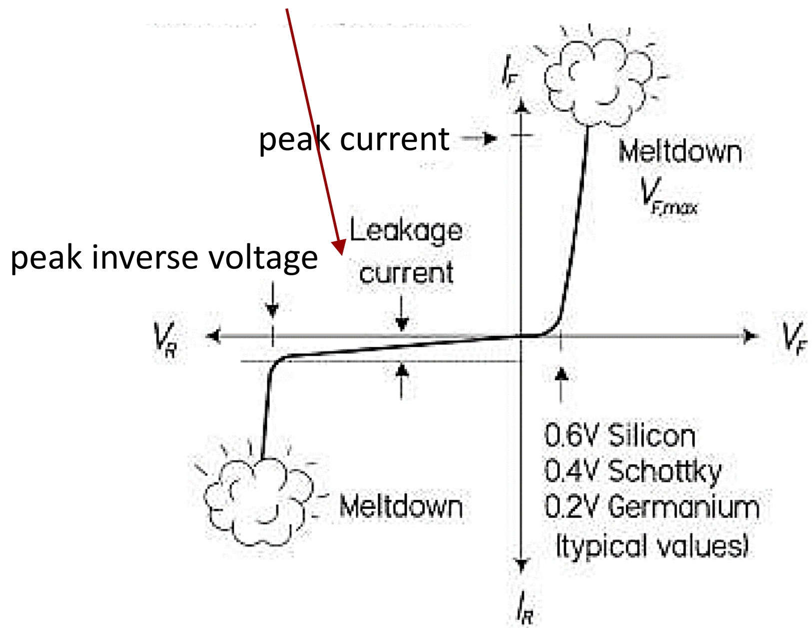


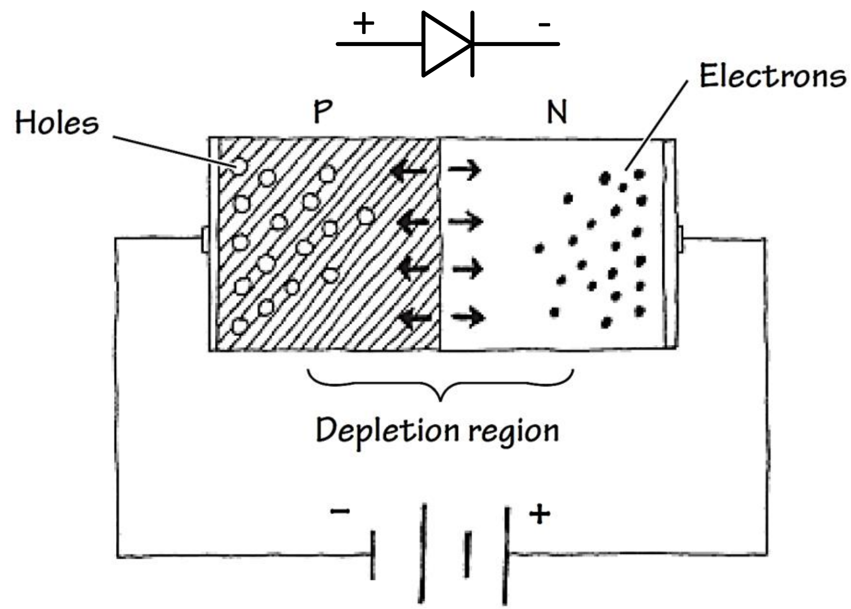
Hence, diode requires a specific voltage to **turn on**.
Thus, they can also act as a voltage-sensitive switch.

Reverse-Biased

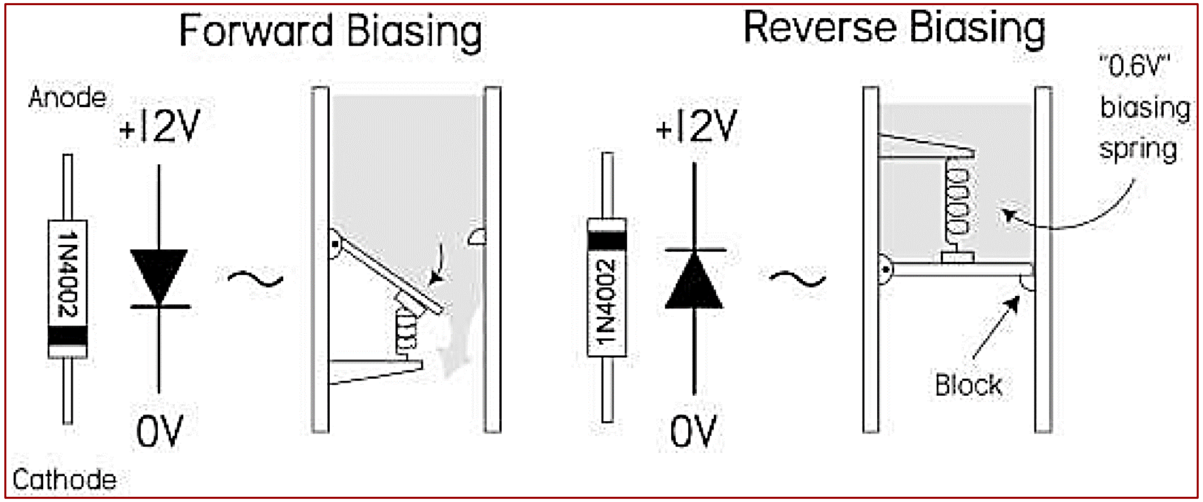
When a diode is connected to a **voltage source** as shown, holes in the n-type side are forced to the left, while electrons in the p-type side are forced to the right. Consequently, the **depletion region enlarges** and **prevents the current flows** through the diode.

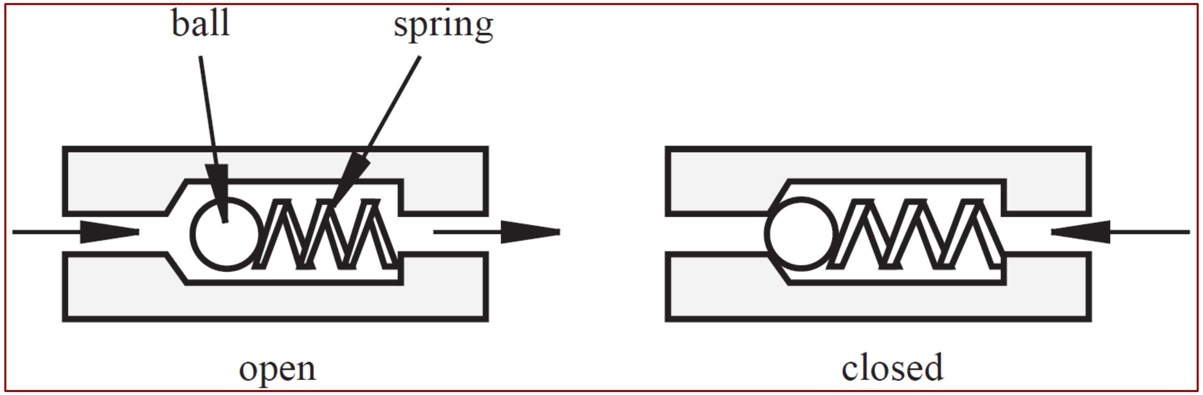
A reverse saturation current (I_0) does flow, but it is **extremely small** (10^{-9} to 10^{-15} A!).



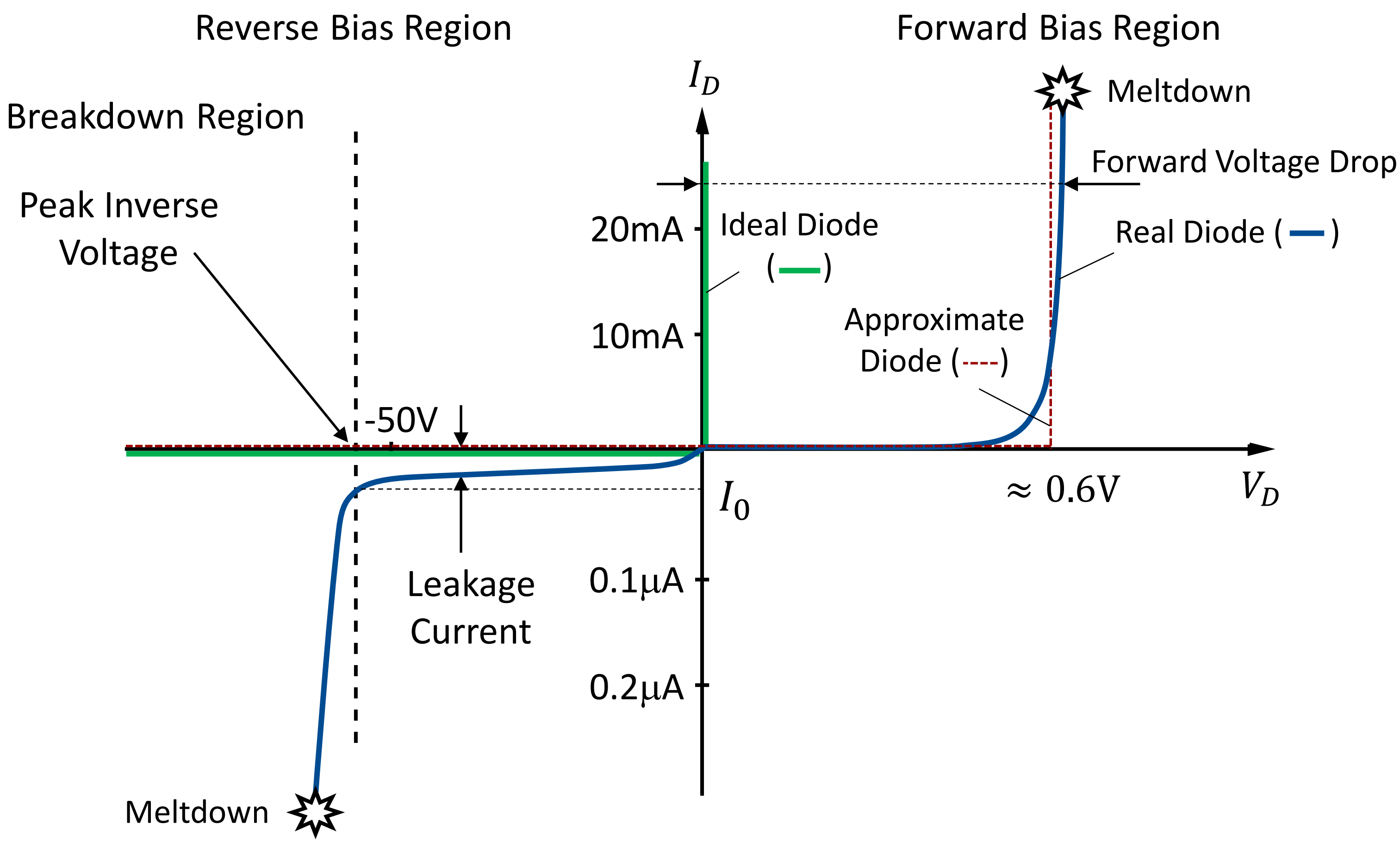


Diode Fluid Analogy





Ideal, Approximate, and Real Diode

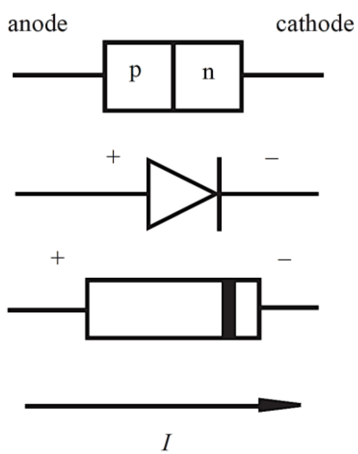


An **ideal diode** has **zero resistance** (short circuit) **when forward biased** and **infinite resistance** (open circuit) **when reverse biased**.

Diode Modeling

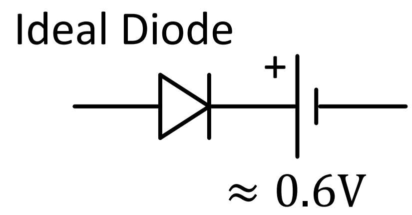
- Modeling of a diode in circuits analysis:

Real Diode



$\cong$

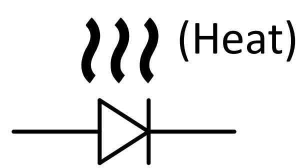
Approximate Diode



(more common model in circuits analysis)

- The heat generated in a diode:

$$P = V_D I_D$$

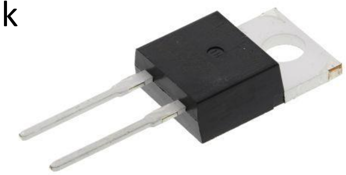


Selection of Diodes

DEVICE	TYPE	PEAK INVERSE VOLTAGE PIV (V)	MAX. FORWARD CURRENT $I_{O\,(MAX)}$	MAX. REVERSE CURRENT $I_{R\,(MAX)}$	PEAK SURGE CURRENT I_{FSM}	MAX. VOLTAGE DROP V_F (V)
1N914	Fast Switch	90	75 mA	25 nA		0.8
1N4148	Signal	75	10 mA	25 nA	450 mA	1.0
1N4445	Signal	100	100 mA	50 nA		1.0
1N4001	Rectifier	50	1 A	0.03 mA	30 A	1.1
1N4002	Rectifier	100	1 A	0.03 mA	30 A	1.1
1N4003	Rectifier	200	1 A	0.03 mA	30 A	1.1
1N4004	Rectifier	400	1 A	0.03 mA	30 A	1.1

- **Power diodes** are capable of carrying very large currents. They are designed to be attached to **heat sinks** in order to efficiently **dissipate heat** produced in the junction.

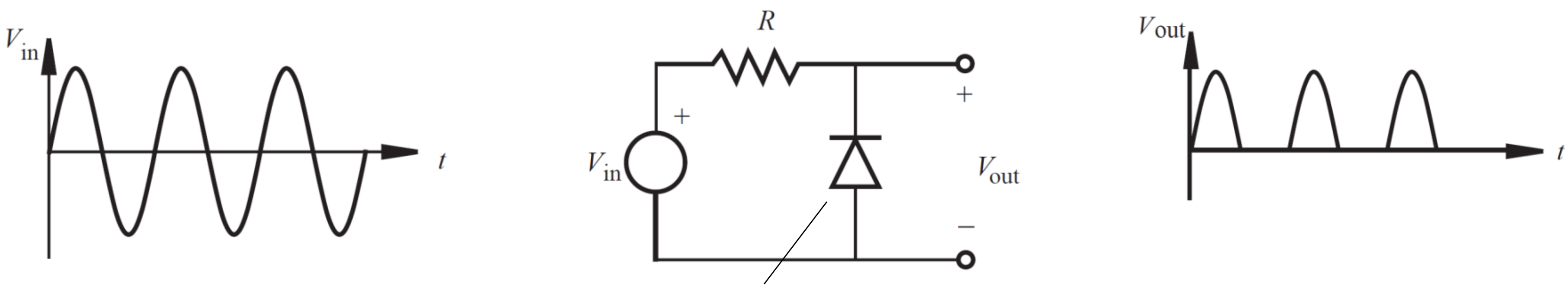
heat sink



Diode Applications

Application: Half-Wave Rectifier

Half-Wave Rectifier is used for passing only the positive (or negative) half of an AC signal. These circuits are used in the design of power supplies, where AC power must be transformed into DC power for use in electronic devices and digital circuits.

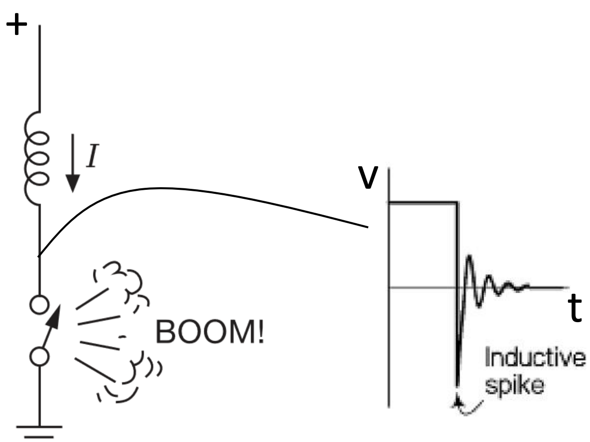


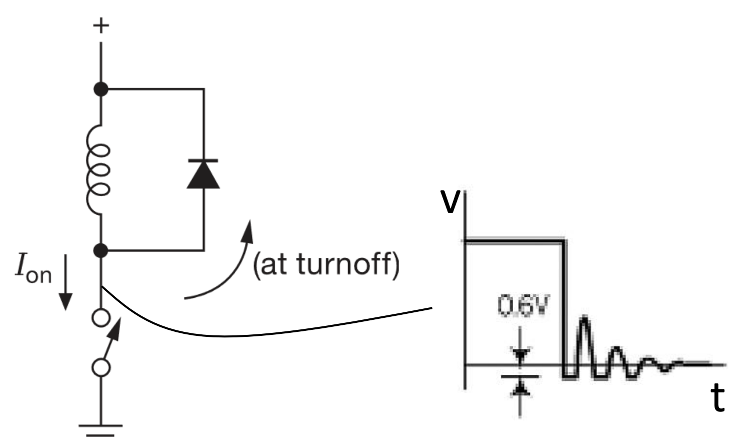
Assumption: **Ideal Diode**

When $V_{\text{in}} > 0$, the diode is reverse biased (open circuit), then output $V_{\text{out}} = V_{\text{in}}$.
When $V_{\text{in}} < 0$, the diode is forward biased (short circuit), then $V_{\text{out}} = 0$.

Application: Fly-Back Diodes

When current flowing through an inductor (e.g., relay coils, motors, solenoids, …) is **suddenly switched off**, the collapsing magnetic field will generate a **high-voltage spike** in the inductor's coils. This spike can damage the switch and can create electromagnetic interference (EMI) that can affect surrounding circuits. A diode placed across the relay's coil can protect neighboring circuitry by providing a short circuit for the high-voltage spike.

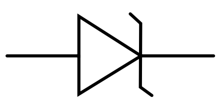




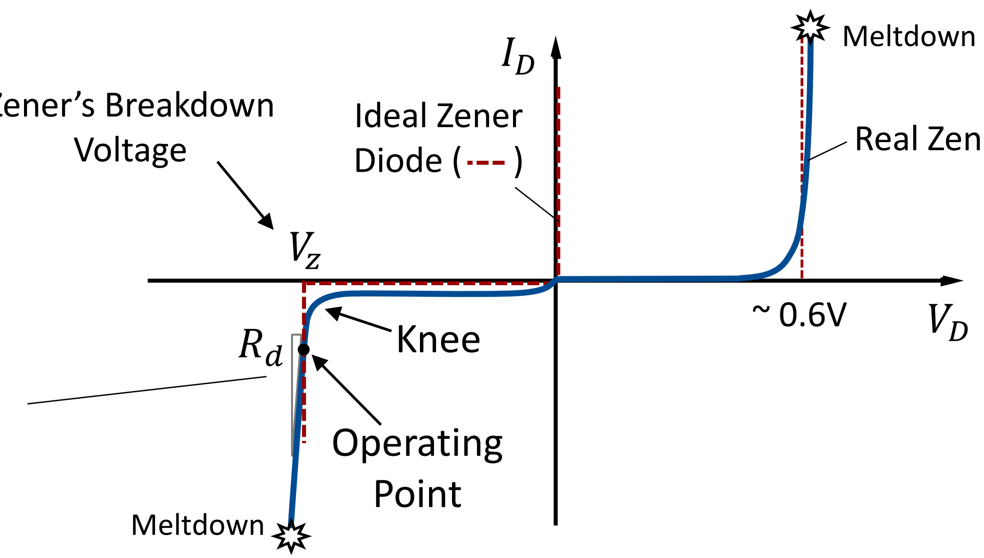
Zener Diode

Zener Diode

When a diode is reverse biased with a large enough voltage, the diode allows a large reverse current to flow. This is called diode breakdown. For most diodes the breakdown value is at least 50 V. However, a special class of diodes known as **Zener**, **avalanche**, or **voltage-regulator diodes** is designed to exhibit **steep breakdown** curves with **well-defined breakdown voltages** (between 1.8 and 200 V). Thus, they can **maintain** a nearly **constant (DC) voltage** in the presence of a **variable supply voltage and variable load** resistance over a wide range of currents. Hence, they are good candidates for building **simple voltage regulators**.



(Schematic Symbol)

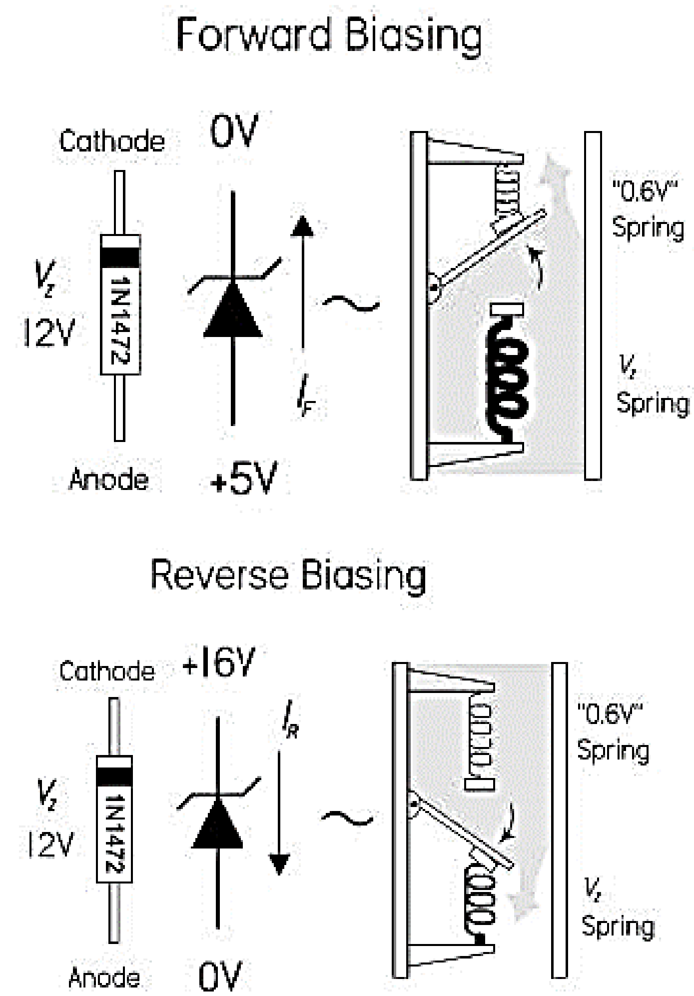


Zener Diode

Some popular Zener diodes:

ZENER VOLTS VZ VOLTS	AXIAL LEAD 500 MW	1 W	5 W
2.4	1N5221B		
2.7	1N5222B		
3.0	1N5225B		
3.3	1N5226B	1N4728A	1N5333B
3.6	1N5227B	1N4729A	1N5334B
3.9	1N5228B	1N4730A	1N5335B
4.3	1N5229B	1N4731A	1N5336B
4.7	1N5230B	1N4732A	1N5337B
5.1	1N5231B	1N4733A	1N5338B
5.6	1N5232B	1N4734A	1N5339B
6.0	1N5233B		1N5340B
6.2	1N5234B	1N4735A	1N5341B
6.8	1N5235B	1N4736A	1N5342B
7.5	1N5236B	1N4737A	1N5343B
8.2	1N5237B	1N4738A	1N5344B
8.7	1N5238B		1N5345B
9.1	1N5239B	1N4739A	1N5346B
10.0	1N5240B	1N4740A	1N5347B
11	1N5241B	1N4741A	1N5348B
12	1N5242B	1N4742A	1N5349B
13	1N5243B	1N4743A	1N5350B
14	1N5244B		1N5351B
15	1N5245B	1N4744A	1N5352B
16	1N5246B	1N4745A	1N5353B
17	1N5247B		1N5354B

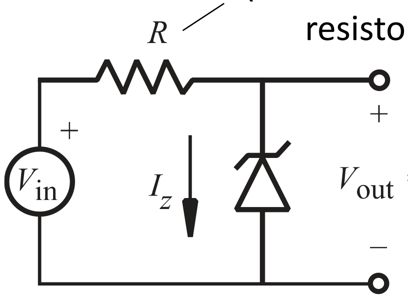
Fluid Analogy:



Zener Diode Voltage Regulator

- To properly use the Zener diode in a circuit, the Zener should be **reverse biased** with a voltage kept in **excess** of its breakdown or Zener voltage V_z.

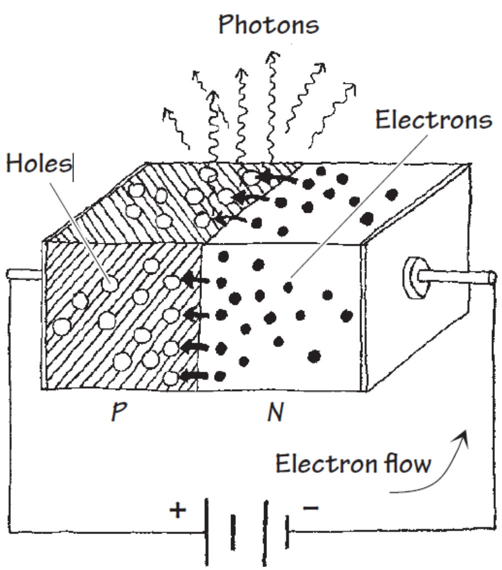
- Using a Zener diode in series with a resistor results in a simple **voltage regulator** in a way that the output voltage V_{out} of the circuit is maintained or regulated by the Zener diode at the Zener voltage V_z.

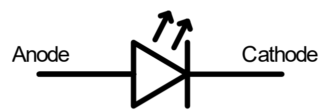


LED

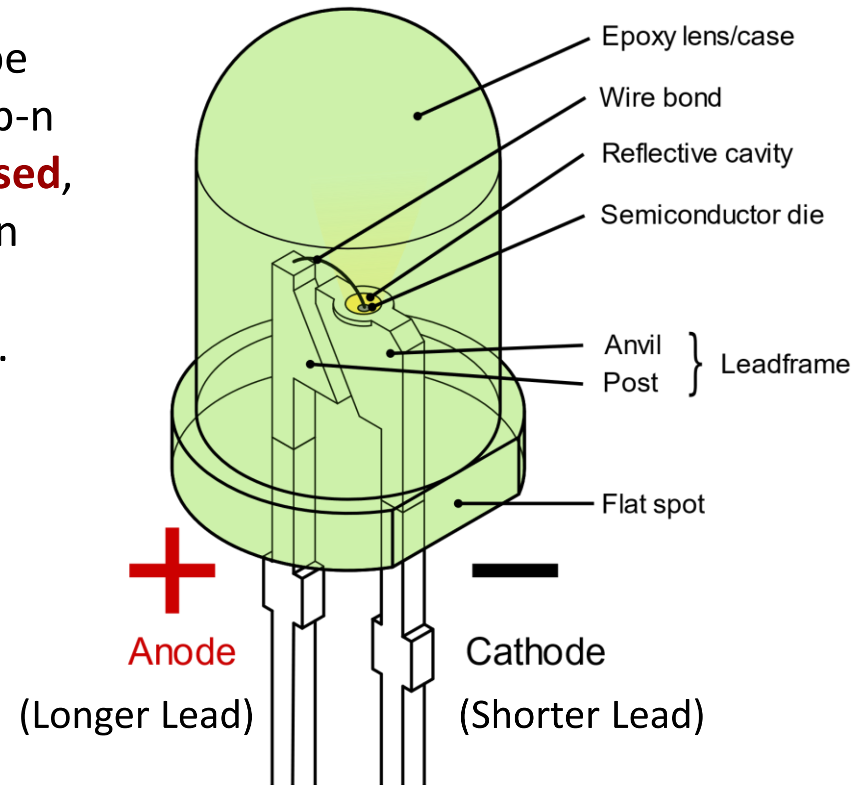
Light-Emitting Diode (LED)

Light-Emitting Diodes are made by joining n-type and p-type semiconductors together to form a p-n junction. When this p-n junction is **forward-biased**, electrons in the n side are **excited** across the p-n junction and move into the p side, where they combine with holes, then, **photons** are emitted.





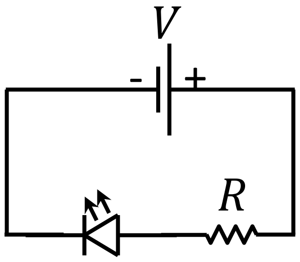
(Symbol)



- LEDs are manufactured to produce a variety of colors.
- They are usually encased in a colored plastic material that enhances the generated wavelength.
- LED has a voltage drop of 1.5 to 2.5 V when forward biased.

A Practical Example

Find a proper resistor (R) which is needed to be wired in series with an LED in the shown circuit when (a) $V = 5\text{ V}$, (b) $V = 9\text{ V}$. Based on the LED's datasheet, the voltage drops across the LED is designed to be 2 V and the maximum current designed to go through an LED is 30 mA.



(a) $V_{\text{LED}} = 2\text{ V} \rightarrow V_{\text{R}} = 5\text{ V} - 2\text{ V} = 3\text{ V}$

$I_{\text{LED}} = 30\text{ mA} \rightarrow I_{\text{R}} = 30\text{ mA}$

$$\begin{cases} R = \dfrac{V_{\text{R}}}{I_R} = 100\ \Omega \\ P_{\text{R}} = V_R I_R = 90\text{ mW} \end{cases}$$

(b) $V_{\text{LED}} = 2\text{ V} \rightarrow V_{\text{R}} = 9\text{ V} - 2\text{ V} = 7\text{ V}$

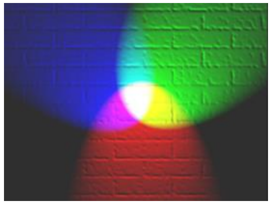
$I_{\text{LED}} = 30\text{ mA} \rightarrow I_{\text{R}} = 30\text{ mA}$

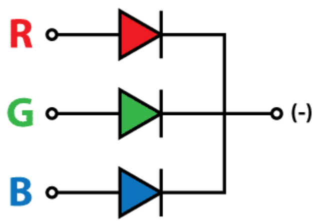
$$\begin{cases} R = \dfrac{V_{\text{R}}}{I_R} = 233.33\ \Omega \\ P_{\text{R}} = V_R I_R = 210\text{ mW} \end{cases}$$

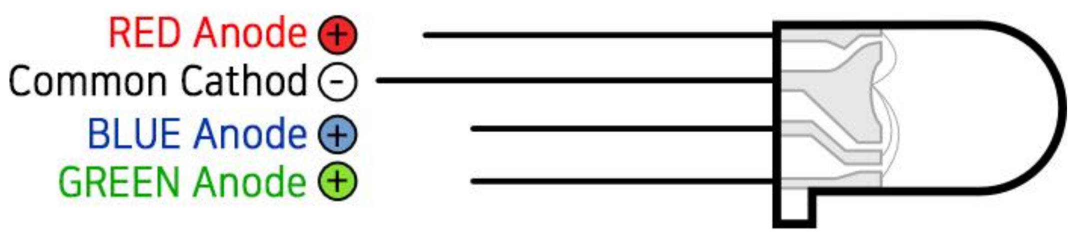
- The **intensity of light** is related to the **amount of current** flowing through the device. However, it is important to include a series **current-limiting resistor** in the circuit to prevent excess forward current, which can quickly destroy the diode.

RGB LEDs

RGB LEDs have four pins. The longest pin is usually a common cathode pin that is shared among all three diodes, while the other three pins connect to the anodes of each diode color, i.e., **Red**, **Green**, and **Blue**.







This LED can be used for **three status** indicators. Moreover, by wiring up the anode pins of this LED to three **PWM** pins of Arduino and changing the brightness of each color, different **mixed colors** can be made.