Ch3: Semiconductor Electronics – Part 1

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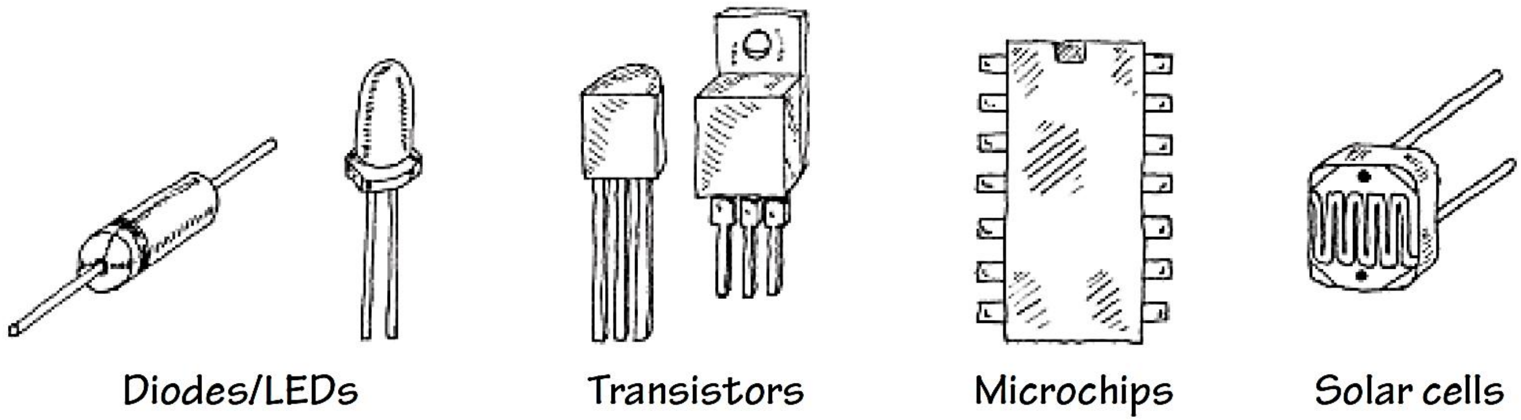
Semiconductor Physics

Semiconductors

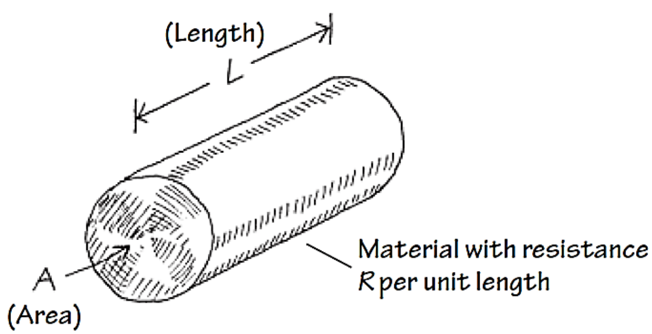
Semiconductors are used extensively in electronic circuits today. Electronic devices, such as **diodes**, **transistors**, **thyristors**, **thermistors**, **photovoltaic cells**, **phototransistors**, **photoresistors**, **lasers**, and **integrated circuits** (ICs), are all made from semiconductive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



Semiconductors

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

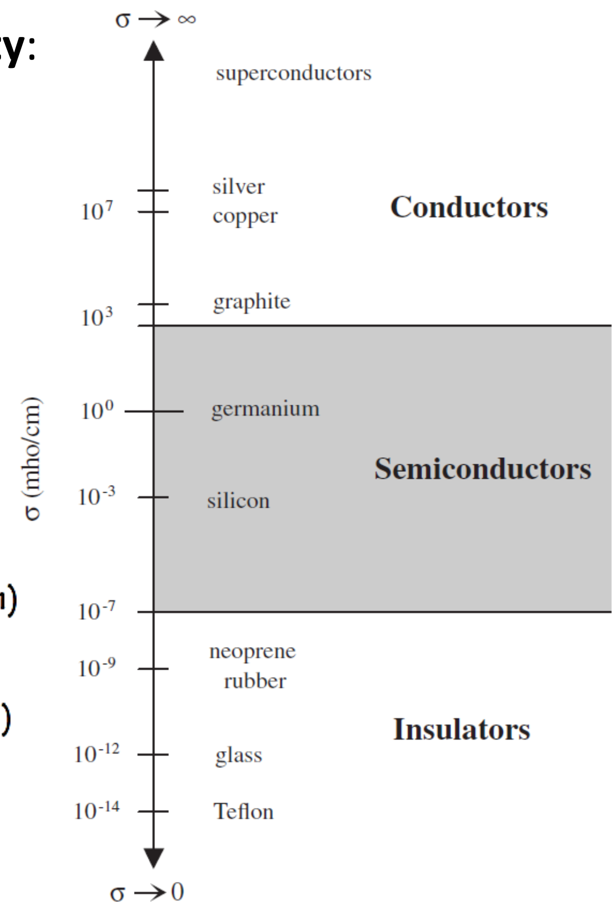
- **Conductors** that easily pass an electric current, such as silver and copper.
- **Insulators** that do not pass an electric current, such as rubber, wood, and glass.
- **Semiconductor** whose conductivity lies between those of conductors and insulators, such as silicon and germanium.



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

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

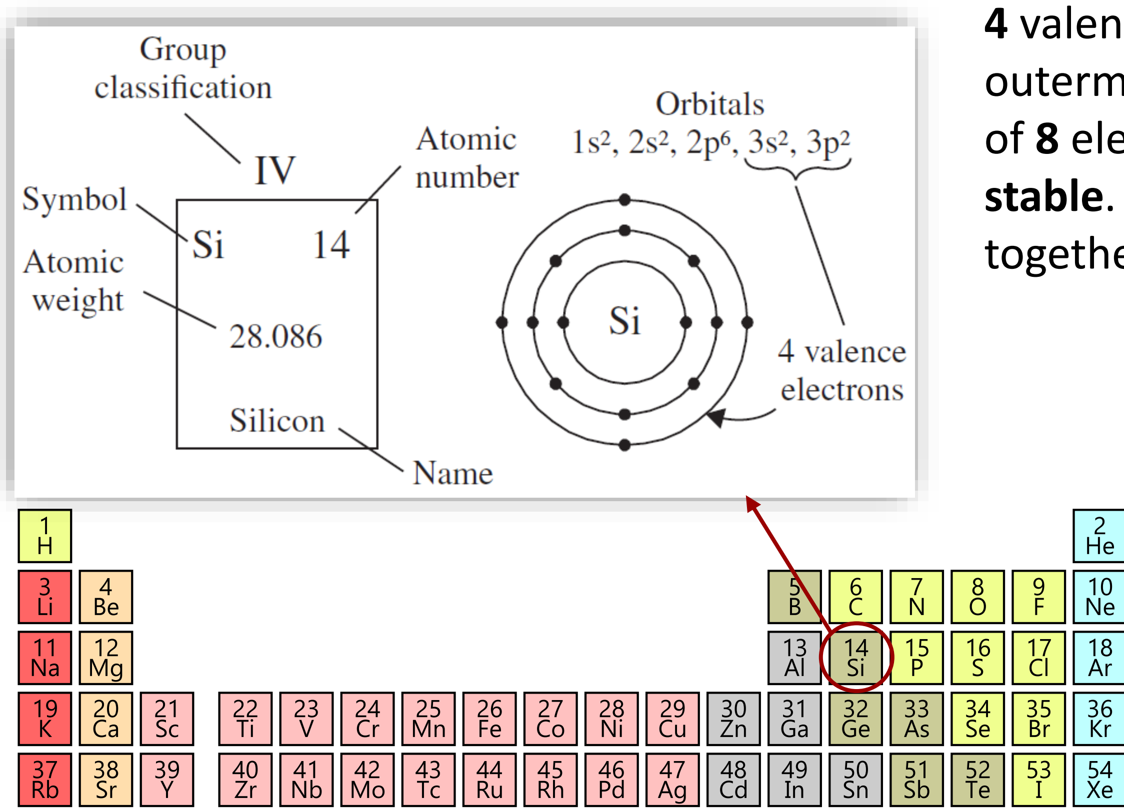
$$\text{mho} = \frac{1}{\text{ohm}} = \frac{1}{\Omega} = \mho$$



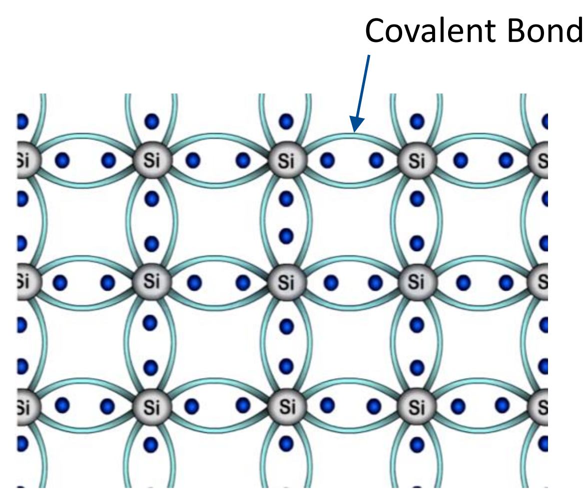
There are two types of **semiconductors** based on their structure: **Intrinsic** and **Extrinsic**.

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**.



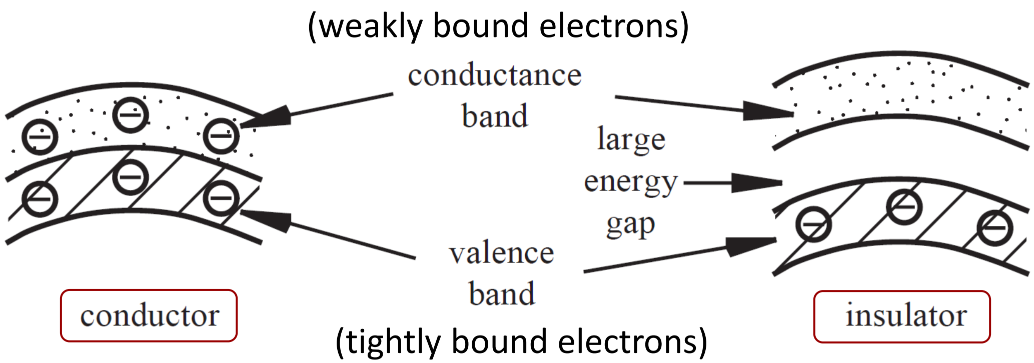
4 valence electrons orbiting in its outermost shell. The atom needs a total of **8** electron in its outer shell to become **stable**. So, silicon atoms are bonded together and form the structure.

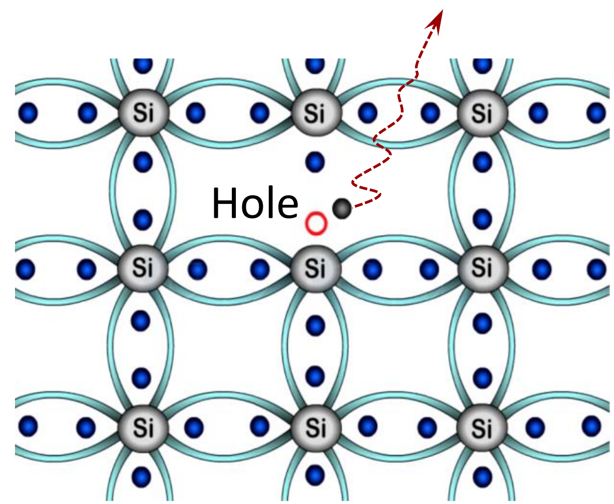


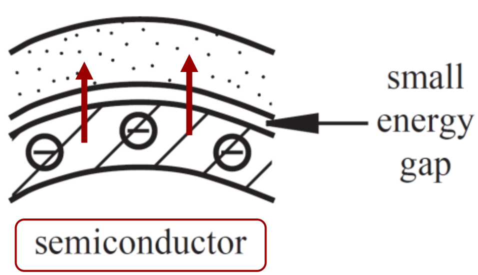
(no free electron)

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**.



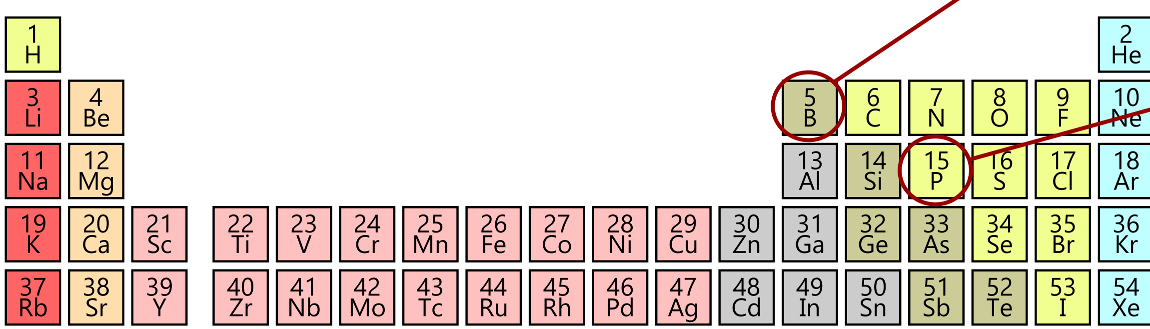


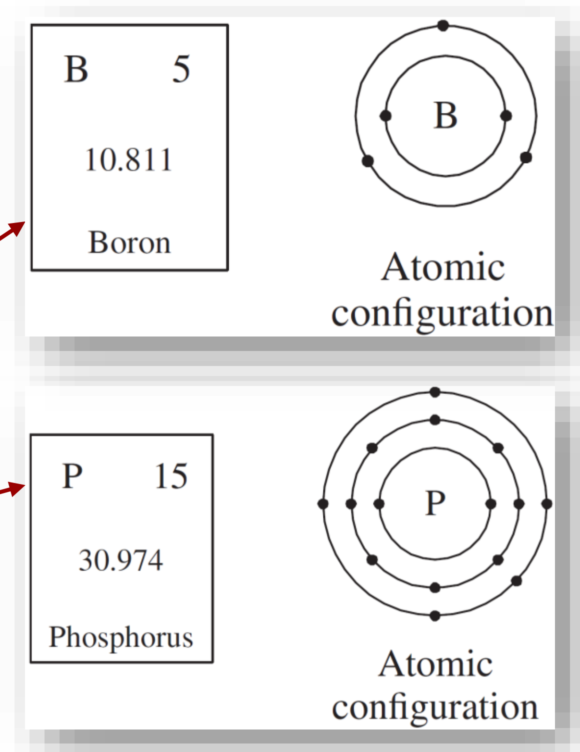


Extrinsic Semiconductors

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**.

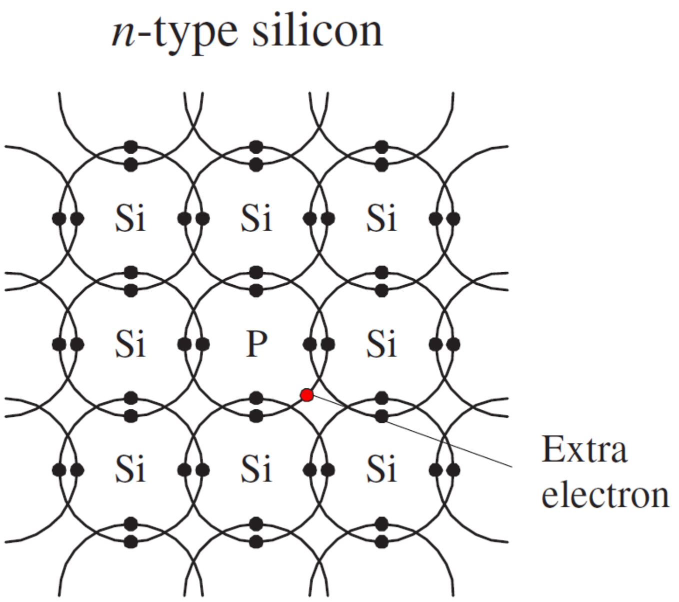
Many ingredients can be added in the doping process. Two of the most important ingredients that can alter the electrical conductivity dramatically are **Phosphorus** (**P**) and **Boron** (**B**).



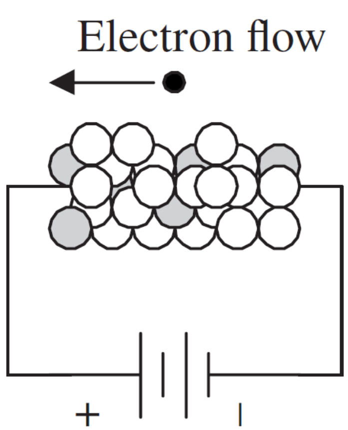


Extrinsic Semiconductors (n-Type)

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**.

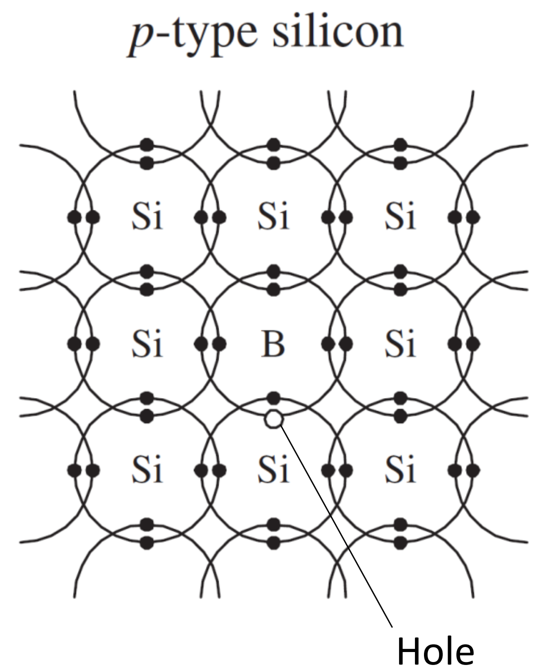


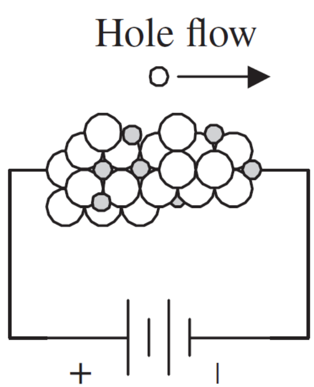
Silicon that is doped with phosphorus is referred to as **n-type silicon**, or **negative-charge-carrier-type** silicon.

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**).

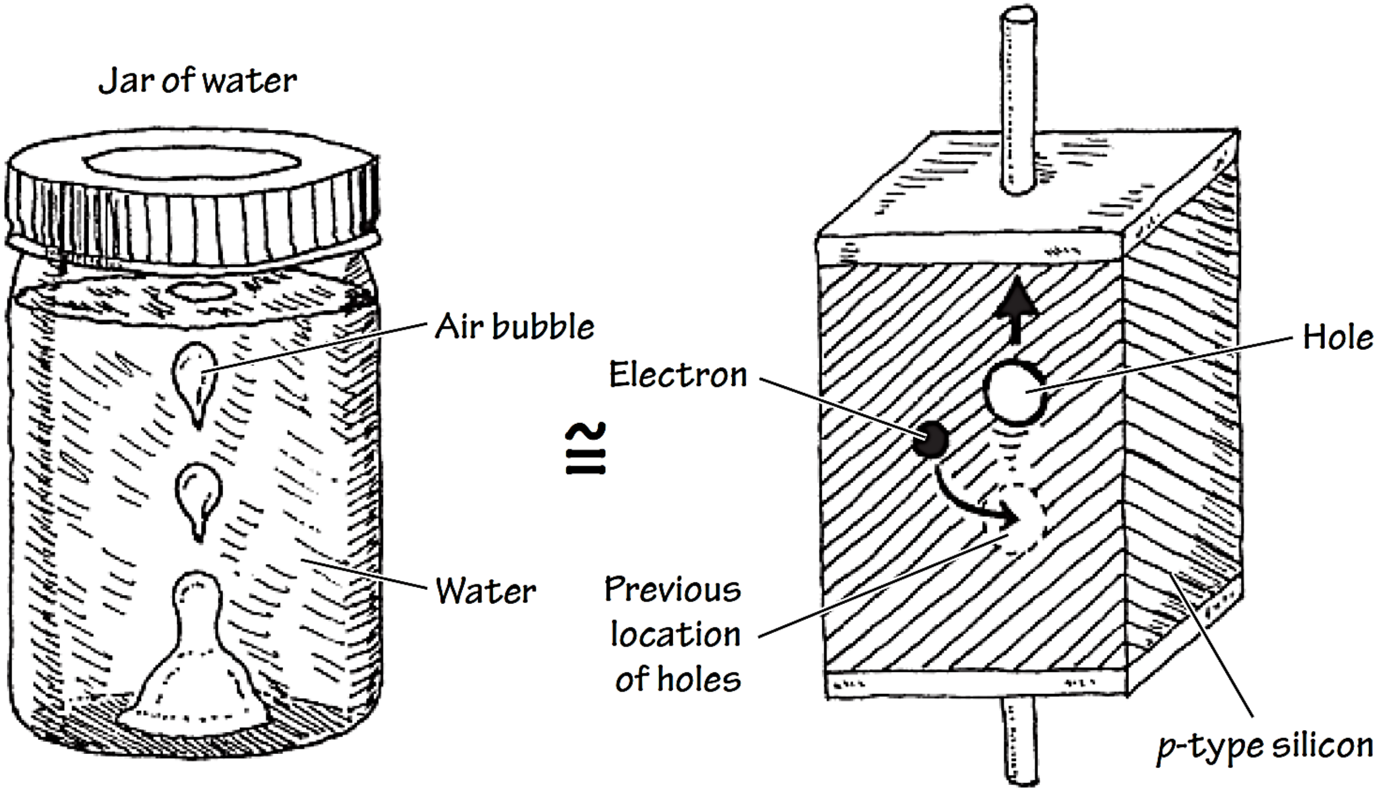




Silicon that is doped with boron is referred to as **p-type silicon**, or **positive-charge-carrier-type** silicon.

How Can Holes Move?

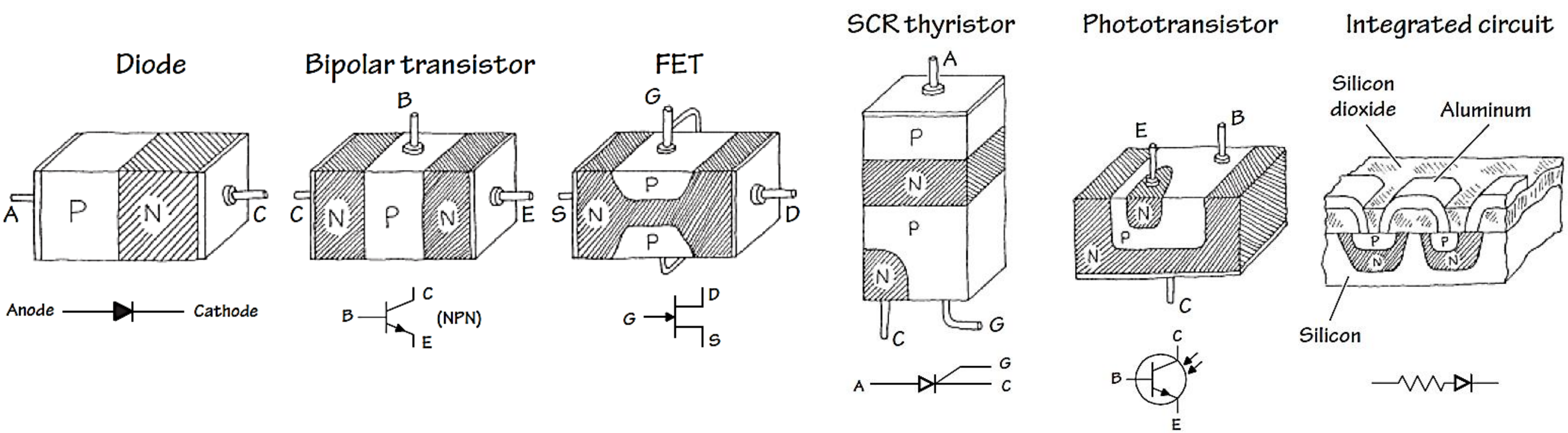
Turn a sealed bottle of water upside down and then right side up. The bubble trapped in the bottle will move in the opposite direction of the water!



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.

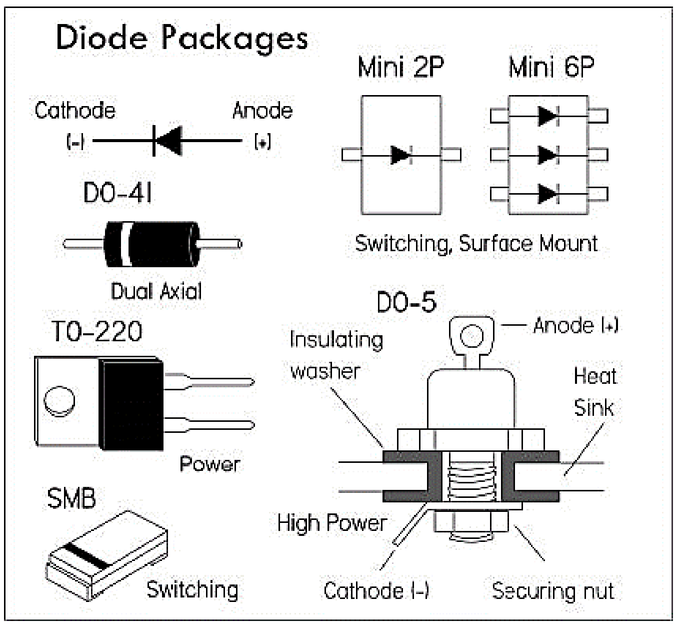


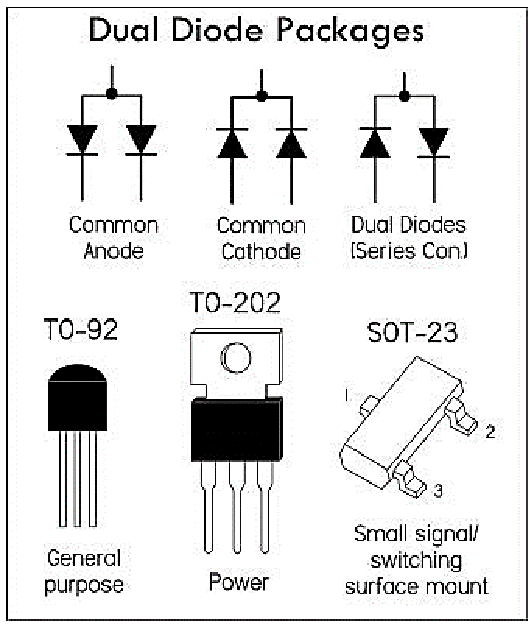
Diodes

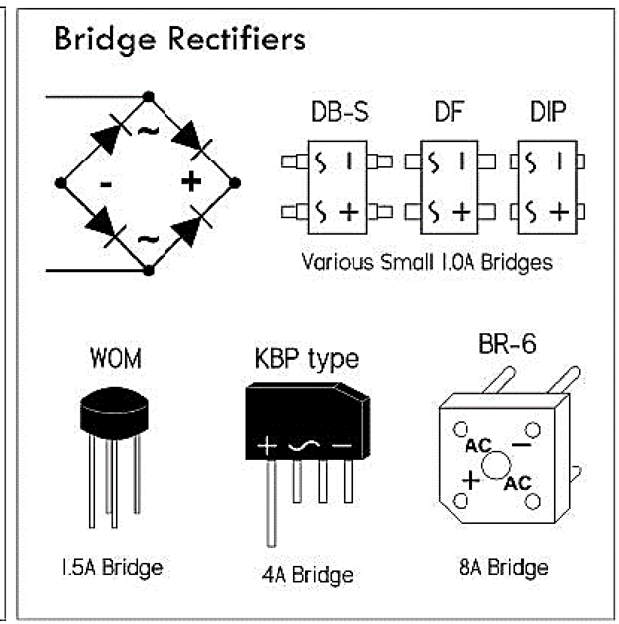
Diode

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.

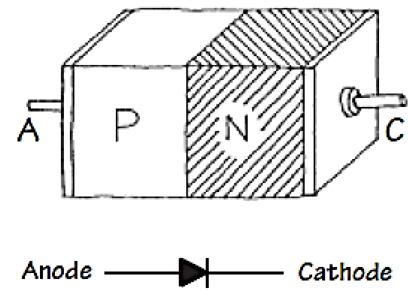




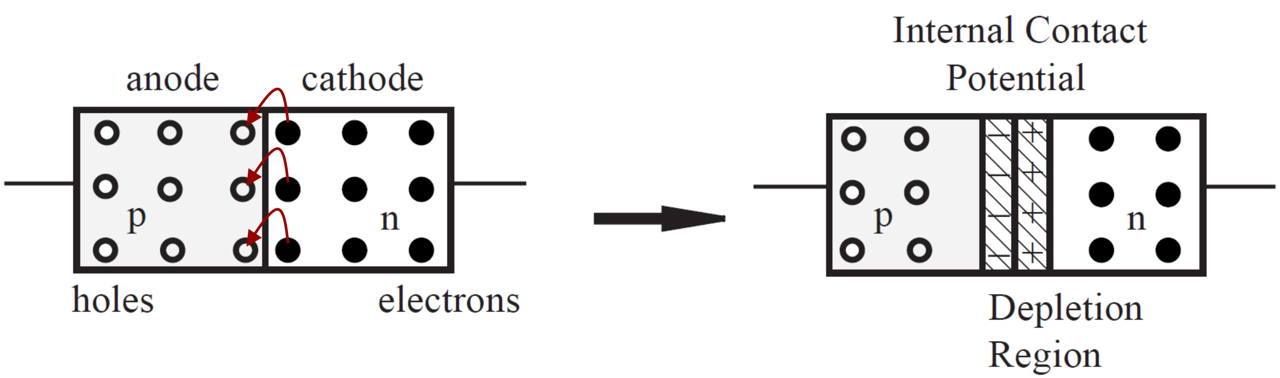


p-n Junction Diode

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** (+).

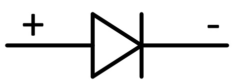


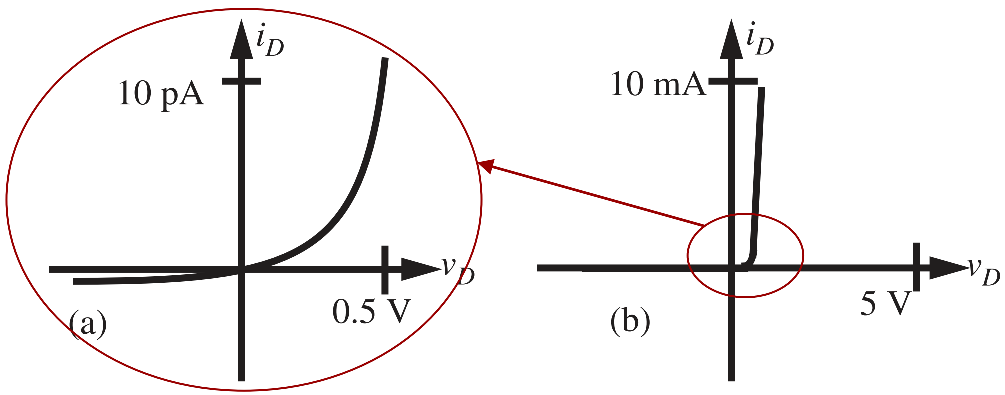
At the p-n junction, electrons from the n-type silicon can diffuse to occupy the holes in the p-type silicon, creating what is called a **Depletion Region**. A **small electric field** develops across this thin depletion region due to the diffusion of electrons. This results in a voltage difference across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

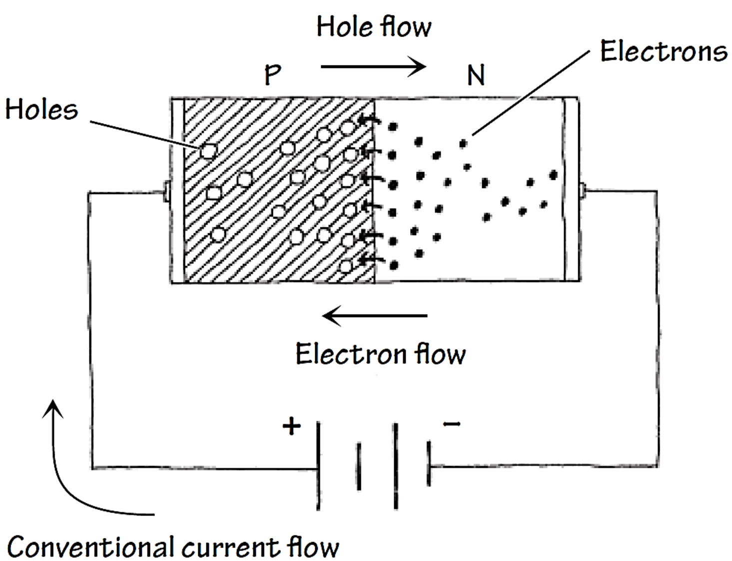


Forward-Biased

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**.





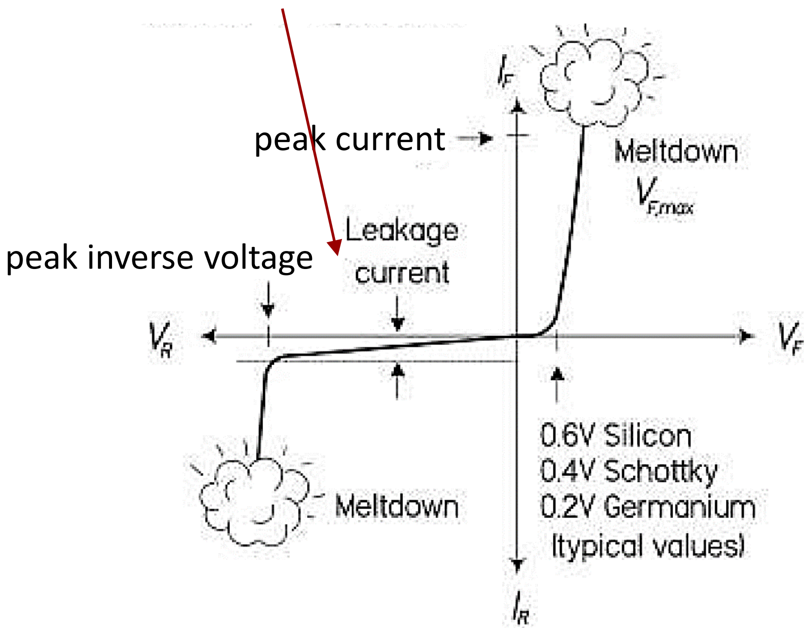


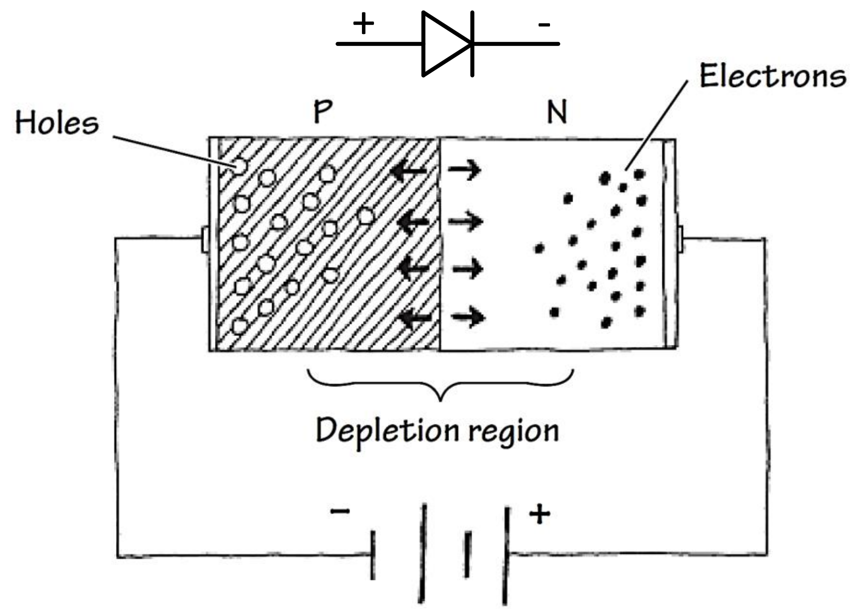
Hence, diode requires a specific voltage to **turn on**.
Thus, they can also act as a voltage-sensitive switch.

Reverse-Biased

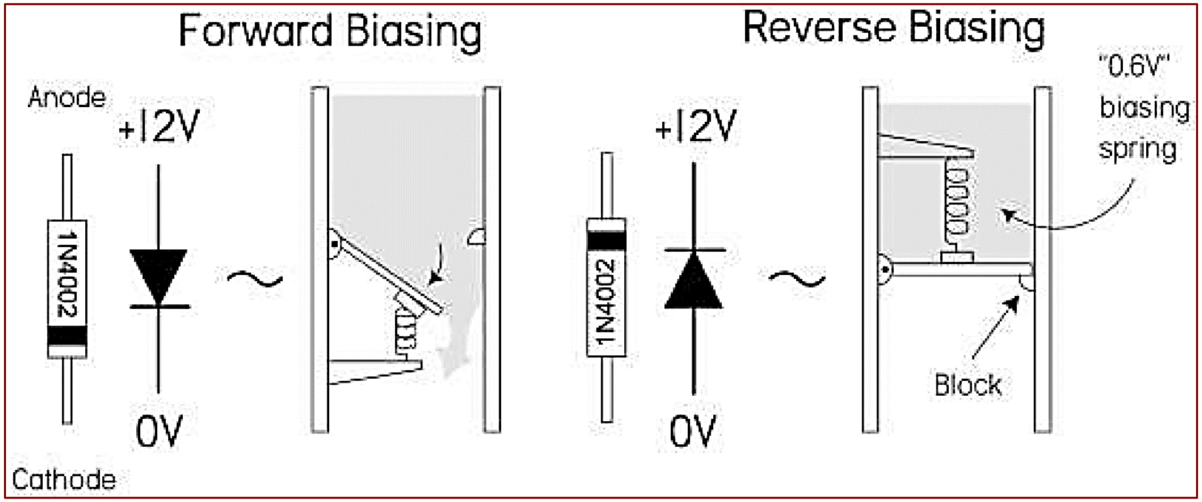
When a diode is connected to a **voltage source** as shown, holes in the n-type side are forced to the left, while electrons in the p-type side are forced to the right. Consequently, the **depletion region enlarges** and **prevents the current flows** through the diode.

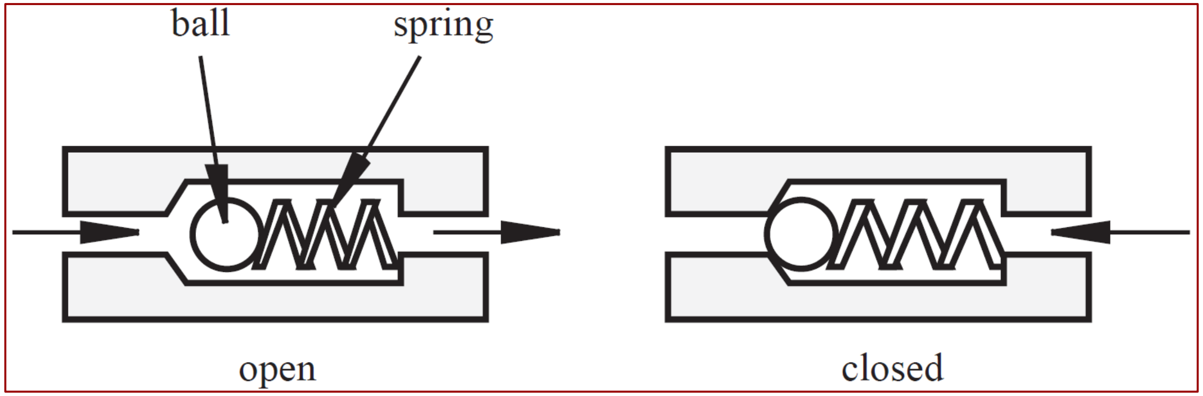
A reverse saturation current (I_0) does flow, but it is **extremely small** (10^{-9} to 10^{-15} A!).



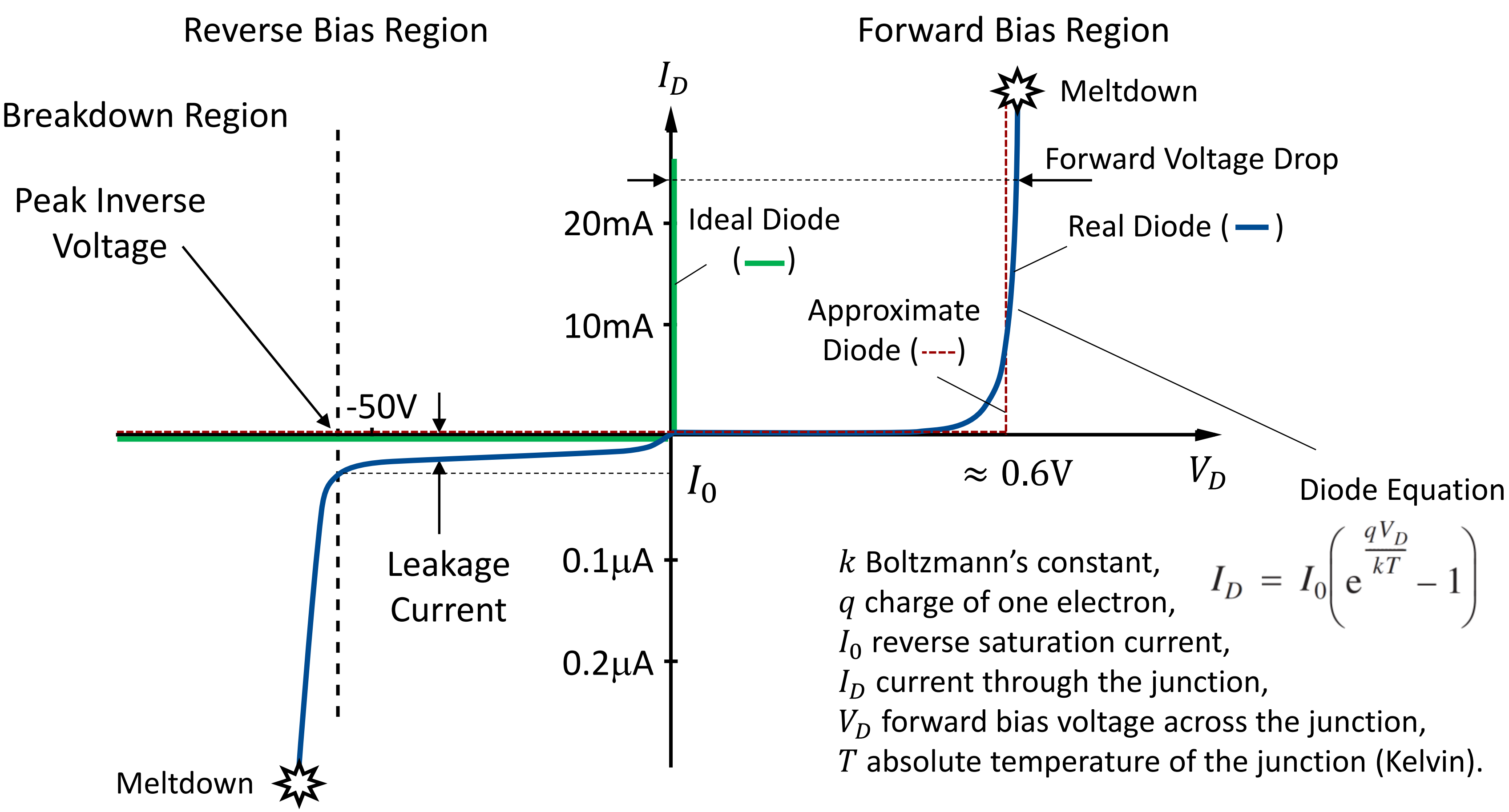


Diode Fluid Analogy





Ideal, Approximate, and Real Diode



Diode Equation:

$$I_D = I_0\left(e^{\frac{qV_D}{kT}} - 1\right)$$

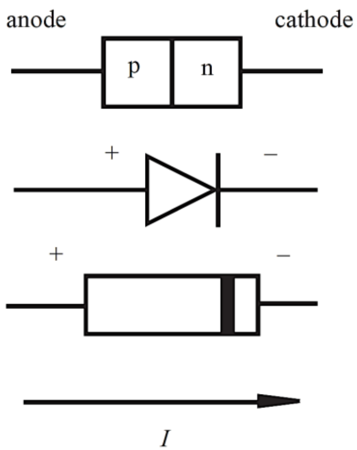
k Boltzmann's constant,
q charge of one electron,
I_0 reverse saturation current,
I_D current through the junction,
V_D forward bias voltage across the junction,
T absolute temperature of the junction (Kelvin).

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:

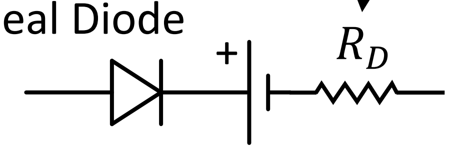
Real Diode



$\cong$

A resistor for modeling nonlinearity of the curve

Ideal Diode



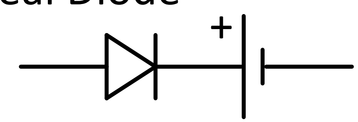
$\approx 0.6\text{V}$

A voltage source for modeling the voltage drop

$\cong$

Approximate Diode

Ideal Diode

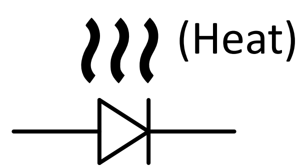


$\approx 0.6\text{V}$

(more common model in circuits analysis)

- The heat generated in a diode:

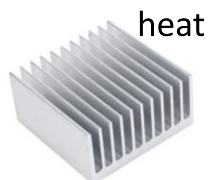
$$P = V_D I_D$$

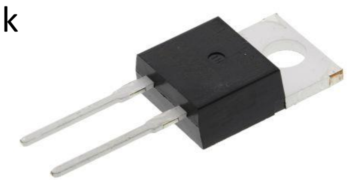


Selection of Diodes

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

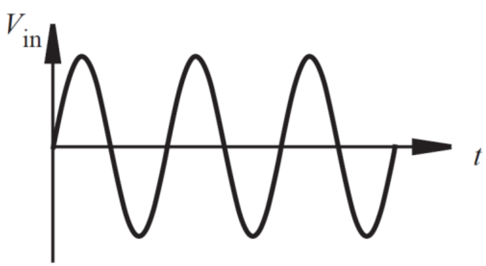
- Diodes require **nanoseconds** to switch between their on and off states. This switching **time** is fast enough for most applications, but when designing high-speed circuits it may pose a constraint.
- **Power diodes** are capable of carrying very large currents. They are designed to be attached to **heat sinks** in order to efficiently **dissipate heat** produced in the junction.

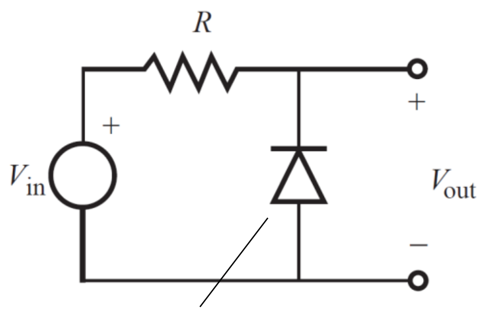


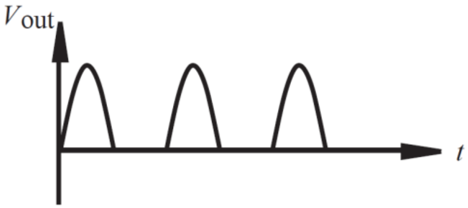


Application: Half-Wave Rectifier

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.







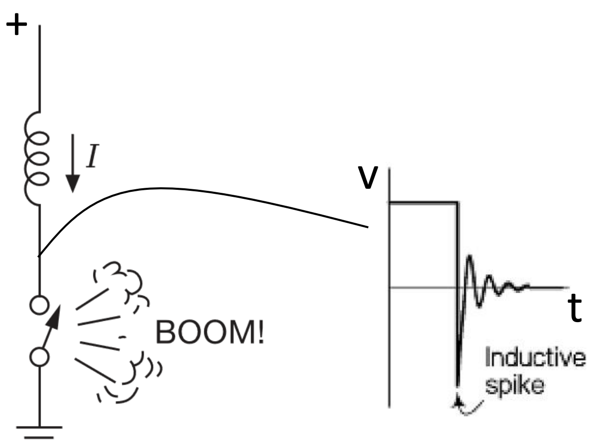
Assumption: **Ideal Diode**

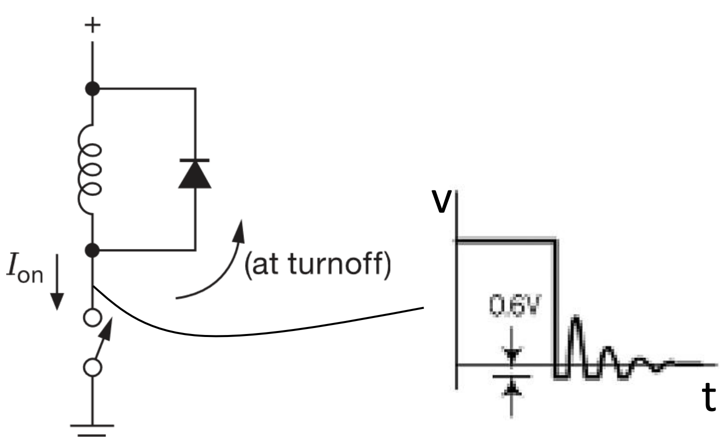
When $V_{in} > 0$, the diode is reverse biased (open circuit), then output $V_{out} = V_{in}$.
When $V_{in} < 0$, the diode is forward biased (short circuit), then $V_{out} = 0$.

❖ How the output would be if **Approximate Diode Curve** is assumed?

Application: Fly-Back Diodes

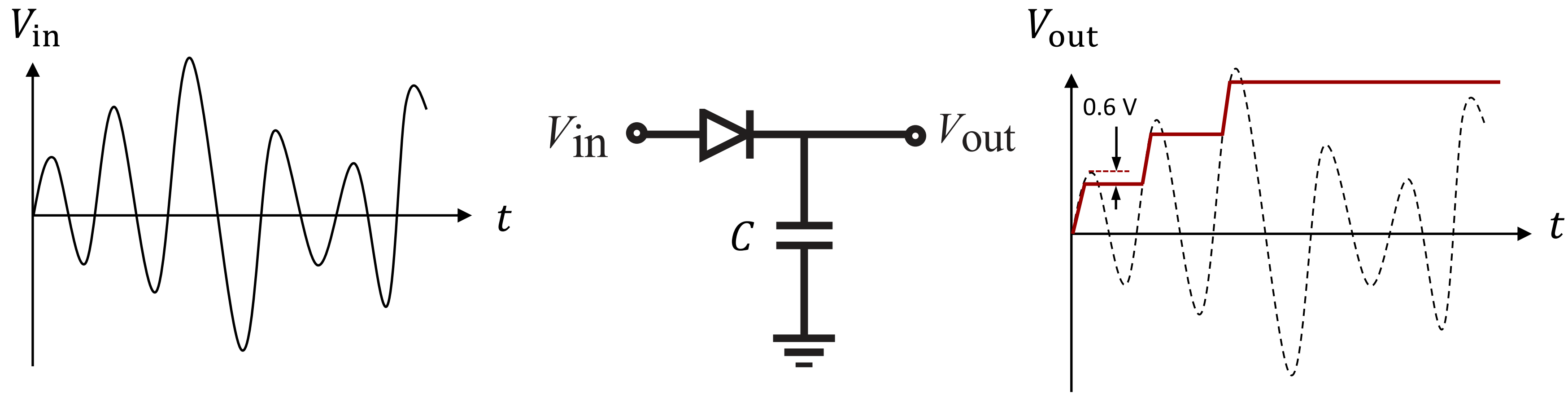
When current flowing through an inductor (e.g., relay coils, motors, solenoids, …) is **suddenly switched off**, the collapsing magnetic field will generate a **high-voltage spike** in the inductor's coils. This spike can damage the switch and can create electromagnetic interference (EMI) that can affect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





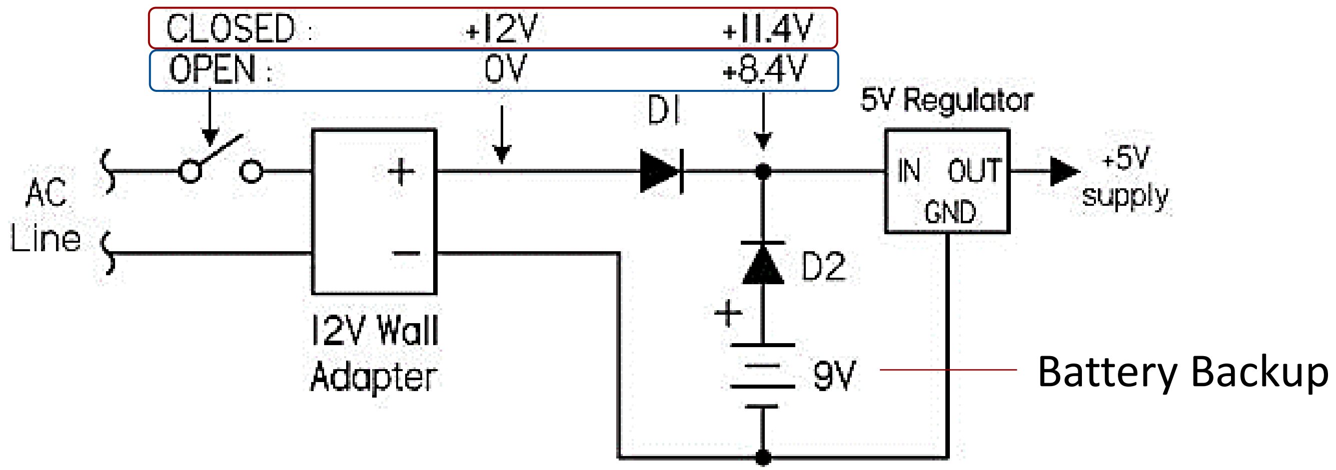
Application: Peak Detector

The following circuit is known as a **peak detector**. When a time-varying signal V_{in} is applied at the input, the output signal V_{out} retains the maximum positive value of the input signal.



Application: Simple Battery Backup

Devices are powered by a wall adapter with battery backup. Normally, if the switch is closed, power is delivered to the load from the 12 V wall adapter through D_1 (note that D_2 is reverse-biased, since its negative end is 2.4V more positive than its positive end). If power is interrupted (switch opened), D_1 stops conducting, and the battery kicks in, sending current through D_2 into the load (D_1 blocks current from flowing back into the wall adapter).



Drawback: There is a penalty (0.6 V) for using diodes for battery backup. You can look for other solutions using transistors and ICs.

Analysis of Diode Circuits

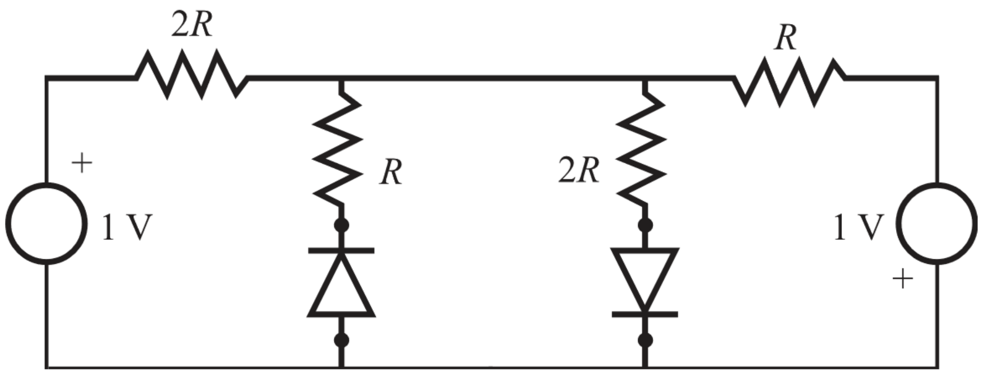
Since the **diode is a nonlinear device**, you can not naively apply the linear circuit analysis methods.

Recommended method:

1. Assume current directions for **each circuit element**.
2. Replace each diode with an equivalent **open circuit** if the assumed current is in a reverse bias direction or a **short circuit** (or a small voltage source) if it is in the forward bias direction.
3. Compute the voltage drops and currents in the circuit loops using KVL and KCL.
4. If the **sign** on a resulting current is **opposite** to the assumed direction through an element, you have made the wrong assumption and must change its direction and **reanalyze** the circuit.
5. Repeat this procedure with **different combinations** of current directions until there are no inconsistencies between assumed and calculated voltage drops and currents.

Example

In the following circuit, determine all currents and voltages. Assume that the diodes are ideals.



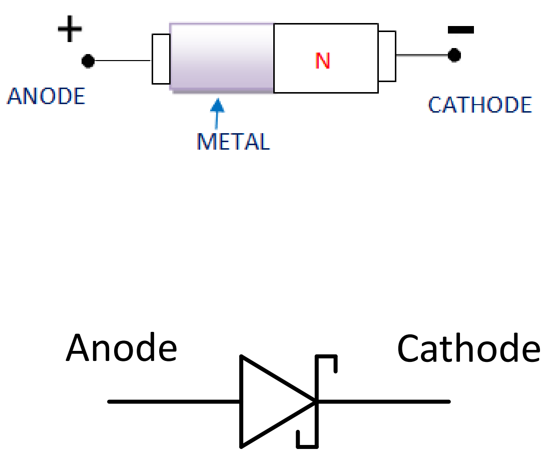
* Now, determine all currents and voltages by using the approximate model of the diodes.

Schottky Diodes

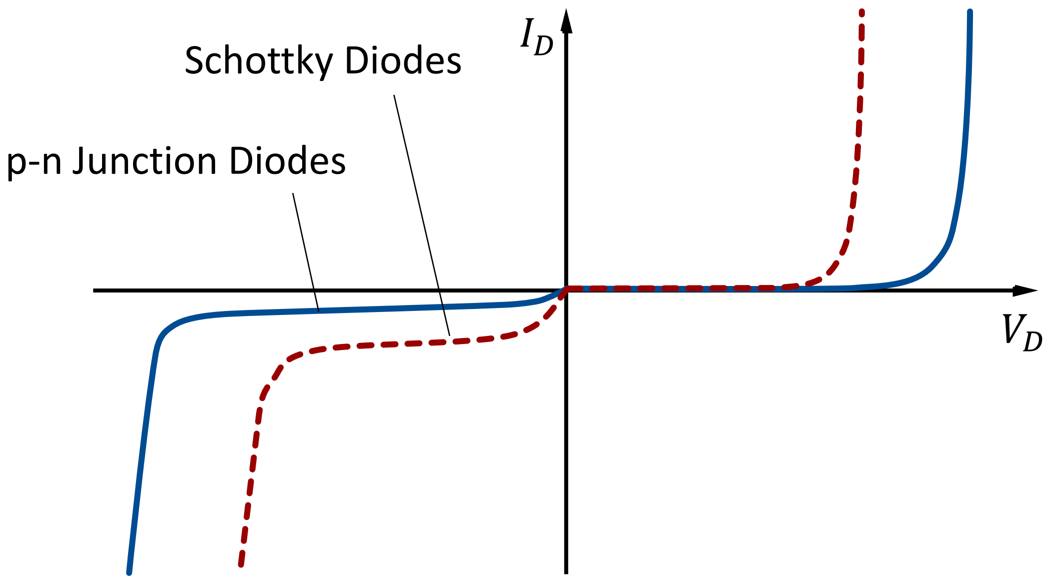
Schottky Diodes are similar in operation to p-n junction diodes but designed with **metal-semiconductor (n-type) junction** instead of a p-n junction. These diodes are used in similar applications as p-n junction diodes, but offer

- Lower forward-bias voltage (0.15 to 0.45 V) ⇒ Lower power loss,
- Quicker switching times (useful in high-frequency applications).

However, they have lower reverse voltage rating and higher reverse leakage current.

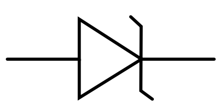


(Schematic Symbol)

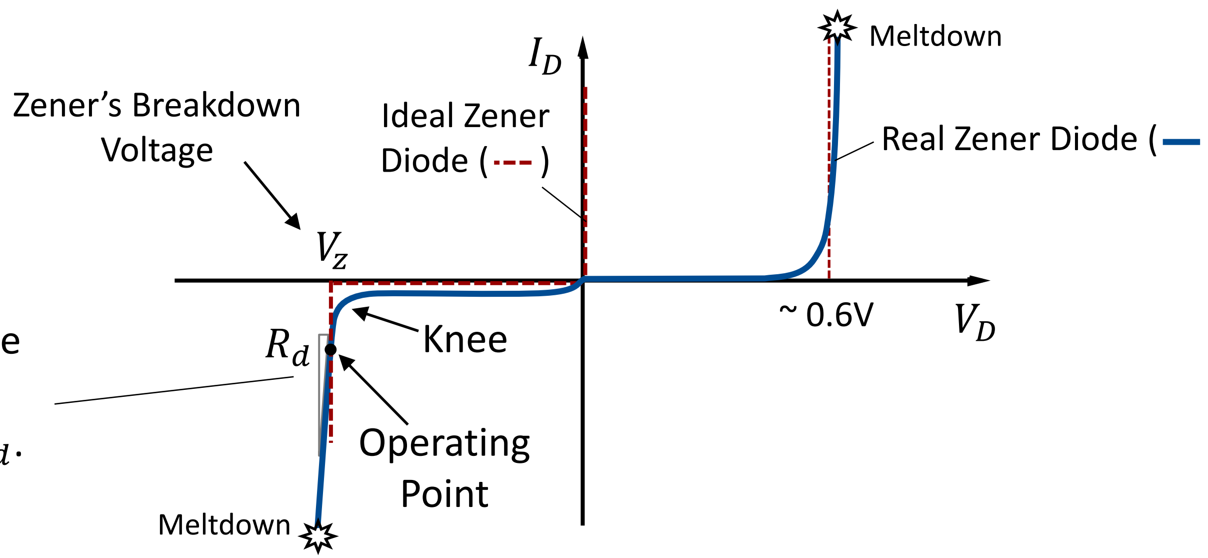


Zener Diode

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)



* The slope of the Zener diode curve at an operating point is called **Dynamic Resistance** R_d.

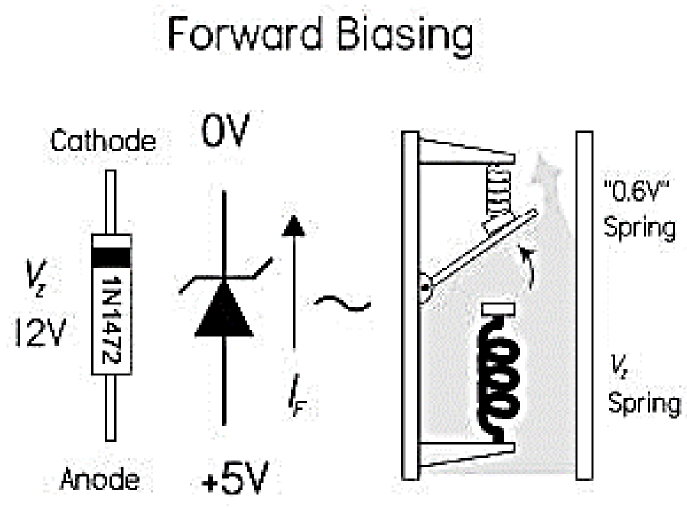
$$R_d = \frac{\Delta V_D}{\Delta I_D}$$

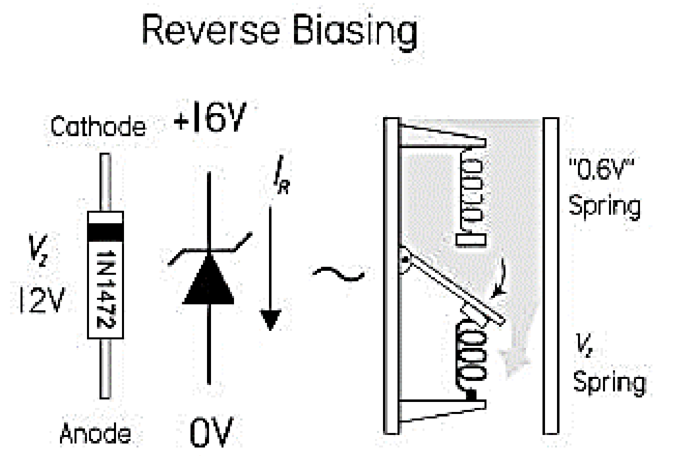
Zener Diode

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:

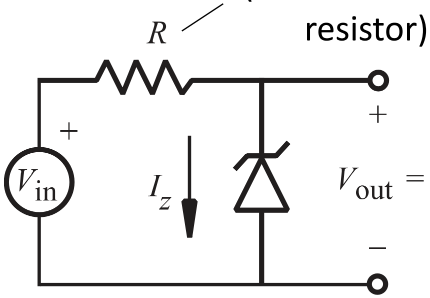




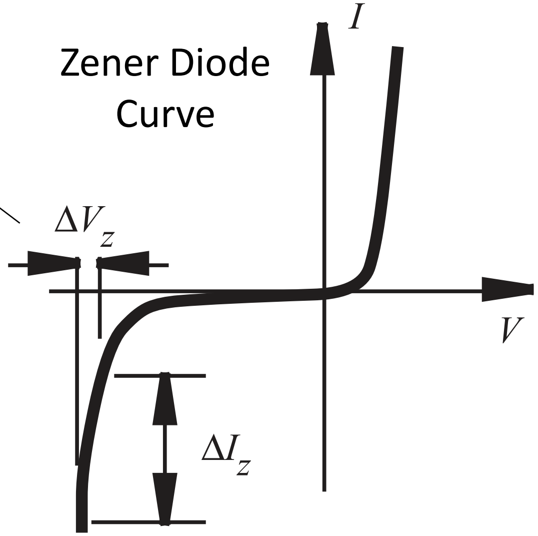
Zener Diode Voltage Regulator

- 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.



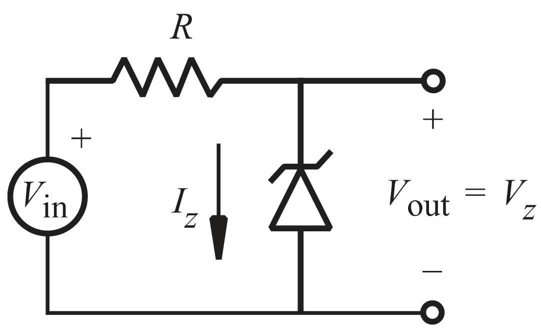
- When the current through the Zener diode changes (ΔI_z), output voltage remains <u>**relatively**</u> constant (ΔV_z is small). ΔV_z is a measure of the voltage regulation of the circuit.

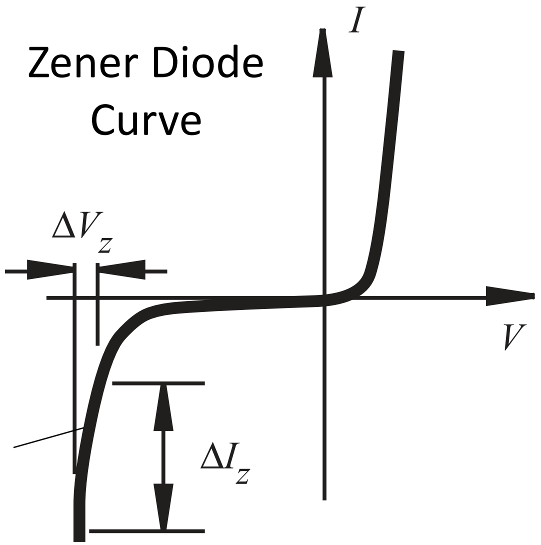


- This simple voltage regulator is more effective, only if the input voltage and load do not change much (see the next example).

Example

Express changes in the regulator output voltage ΔV_{out} in terms of fluctuations in the source voltage ΔV_{in}.



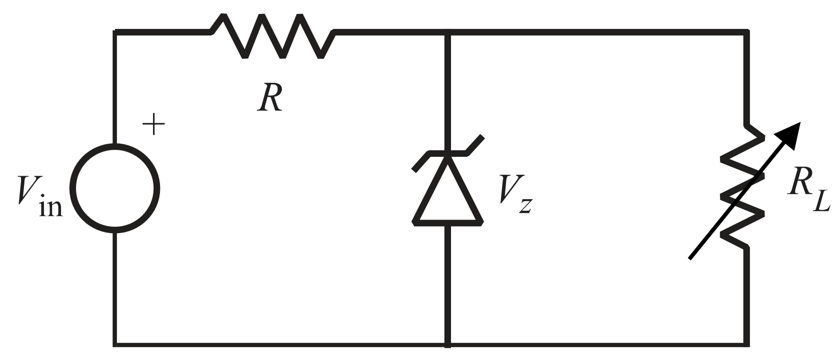


$$R_d = \frac{\Delta V_z}{\Delta I_z}$$

Example: Zener Diode Voltage Regulator Design

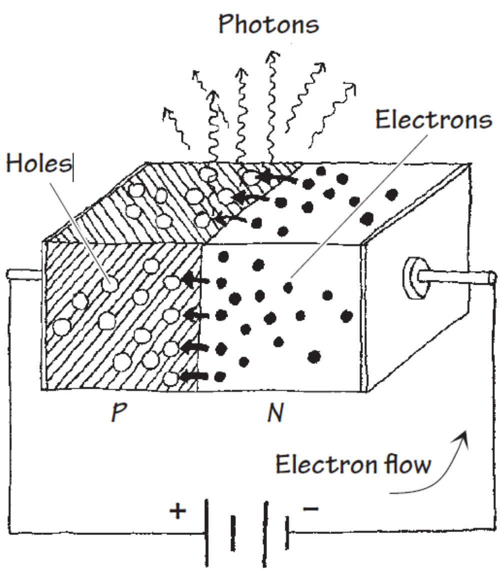
Suppose we need to design a regulated 15 V DC source to power a mechatronic system, and we would like to use the following voltage regulator circuit. Furthermore, suppose we have access to only a poorly regulated DC source V_{in} whose nominal value is 24 V (assume that the Zener diode is ideal). Find the minimum required current-limiting resistance R.

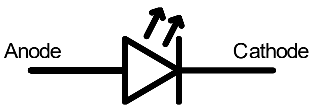
Maximum value of the load $R_{L_{\max}}$ is 240 Ω, and we want to select a 1 W Zener diode.



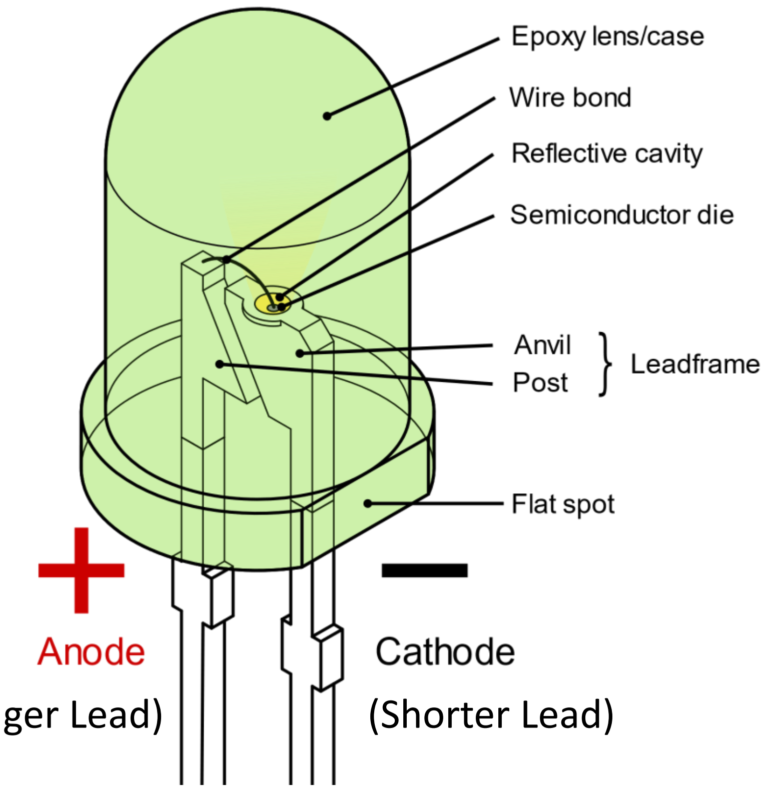
Light-Emitting Diode (LED)

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.





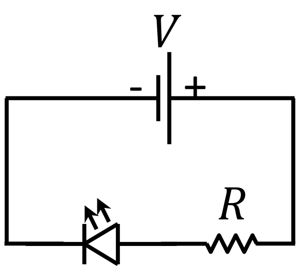
(Symbol)



- 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) $V = 5\ \mathrm{V}$, (b) $V = 9\ \mathrm{V}$. Based on the LED's datasheet, the voltage drops across the LED is designed to be $2\ \mathrm{V}$ and the maximum current designed to go through an LED is $30\ \mathrm{mA}$.



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

$I_{\mathrm{LED}} = 30\ \mathrm{mA} \longrightarrow I_{\mathrm{R}} = 30\ \mathrm{mA}$

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

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

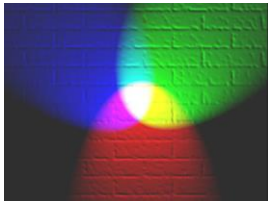
$I_{\mathrm{LED}} = 30\ \mathrm{mA} \longrightarrow I_{\mathrm{R}} = 30\ \mathrm{mA}$

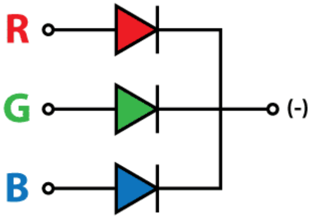
$$\begin{cases} R = \dfrac{V_{\mathrm{R}}}{I_R} = 233.33\ \Omega \\ P_{\mathrm{R}} = V_R I_R = 210\ \mathrm{mW} \end{cases}$$

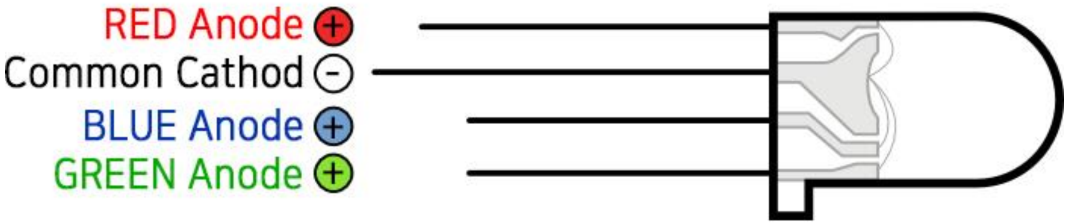
- The **intensity of light** is related to the **amount of current** flowing through the device. However, it is important to include a series **current-limiting resistor** in the circuit to prevent excess forward current, which can quickly destroy the diode.

RGB LEDs

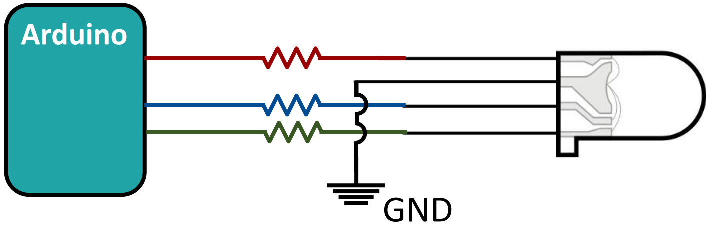
RGB LEDs have four pins. The longest pin is usually a common cathode pin that is shared among all three diodes, while the other three pins connect to the anodes of each diode color, i.e., **Red**, **Green**, and **Blue**.







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.



Bipolar Junction Transistors (BJTs)

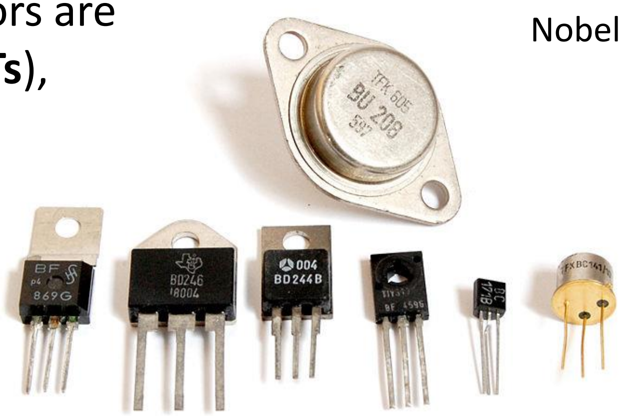
Transistors

Transistor is one of the greatest inventions of the 20th century (1947) [Transfer + resistor → Transistor].

- Transistors are semiconductor devices that act as either **electrically controlled switches** (digital electronics) or **linear amplifier** (analogue electronics).

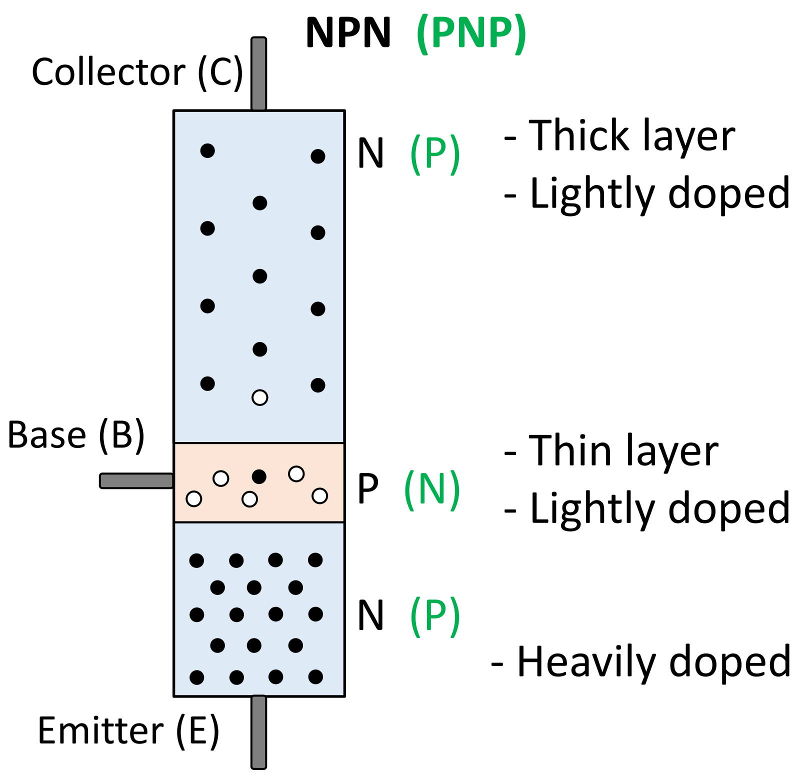
J. Bardeen, W. Shockley, W. Brattain
Invention: 1947
Nobel Prize: 1956

The two major families of transistors are
- **Bipolar Junction Transistors** (**BJTs**),
- **Field-Effect Transistors** (**FETs**).



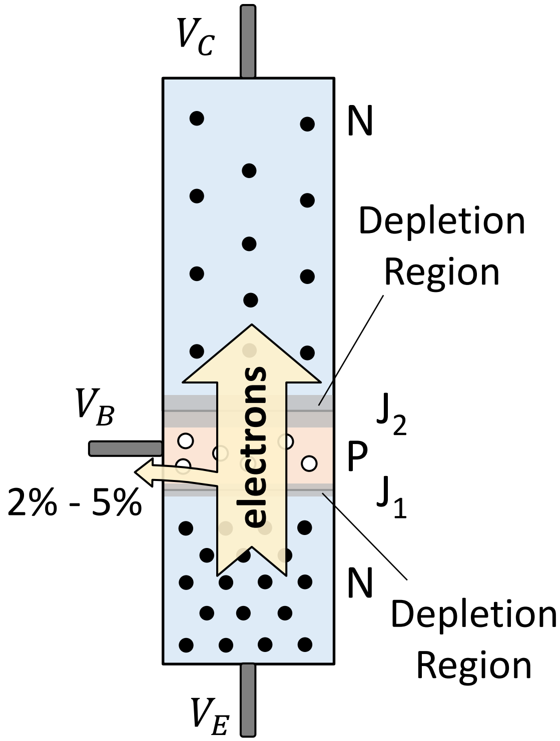
Bipolar Junction Transistor (BJT)

A **Bipolar Junction Transistor** (**BJT**) consists of three adjacent regions of doped silicon, each of which is connected to an external lead (i.e., **Collector**, **Base**, and **Emitter**). There are two types of BJTs: **npn** and **pnp** transistors (**npn** is the most common type).



How NPN BJT Work?

In order to operate the transistor in **active mode**, the junction J_1 must be **forward biased** ($V_B > V_E$) and junction J_2 must be **reversed biased** ($V_C > V_B$). Thus, the depletion regions which tend to prevent the flow of electrons are created.

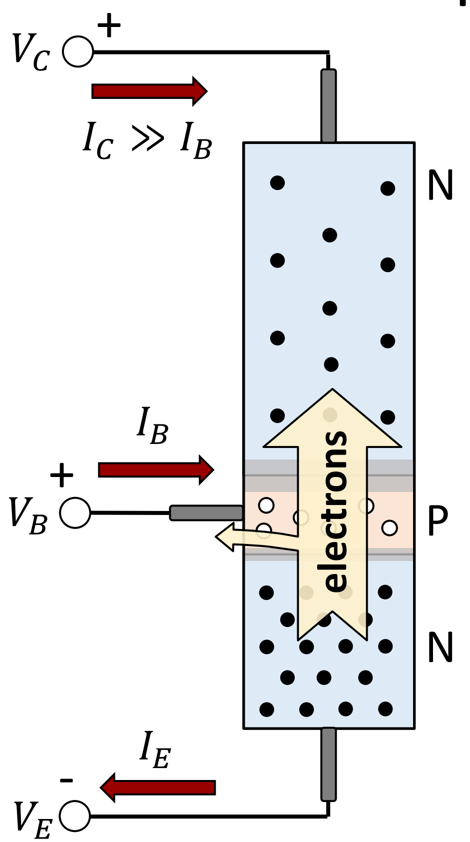


If a voltage is applied to the base so that $V_{BE} \approx +0.7\text{V}$, electrons diffuse from the emitter region to the base region through J_1:

- 2-5% of them recombine with the holes and form the base current I_B.
- Since the base region is very thin and lightly doped and the emitter region is heavily doped, 95-98% of the electrons from the emitter accelerate through the base region with enough momentum to cross the depletion region J_2 into the collector region without recombining with holes in the base region and form the collector current I_C.

How NPN BJT Work?

Thus, in **active mode**, small base current I_B flows from the base to the emitter controls a larger current $I_C \gg I_B$ flows from the collector to the emitter, and therefore, the BJT functions as a current **amplifier**.



$$I_C = h_{\mathrm{FE}} I_B = \beta \mathrm{I}_B$$

β is **current gain**.

$$I_E = I_C + I_B$$

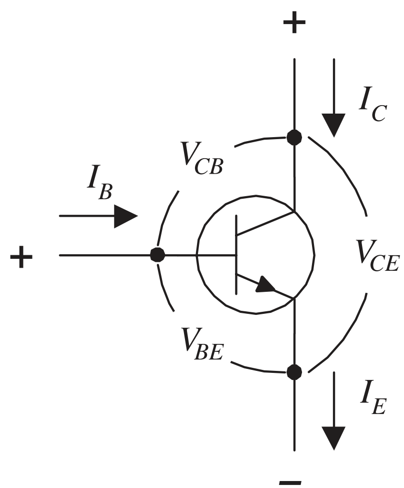
In summery, when $V_{BE} = V_B - V_E \approx 0.7\mathrm{V}$, the transistor is **on** and a **large** collector current I_C can flow with a **small** base current I_B.

Note: Conventional currents are moving in the opposite direction to the electron flow.
Note: For a pnp bipolar transistor, all ingredients, polarities, and currents are **reversed**.

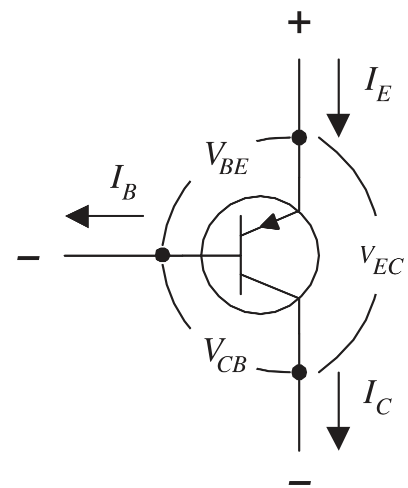
NPN & PNP BJT

A **npn** bipolar transistor uses a small input current and positive voltage at its base (relative to its emitter) to control a much larger **collector-to-emitter** current.

A **pnp** transistor uses a small output base current and negative base voltage (relative its emitter) to control a larger **emitter-to-collector** current.



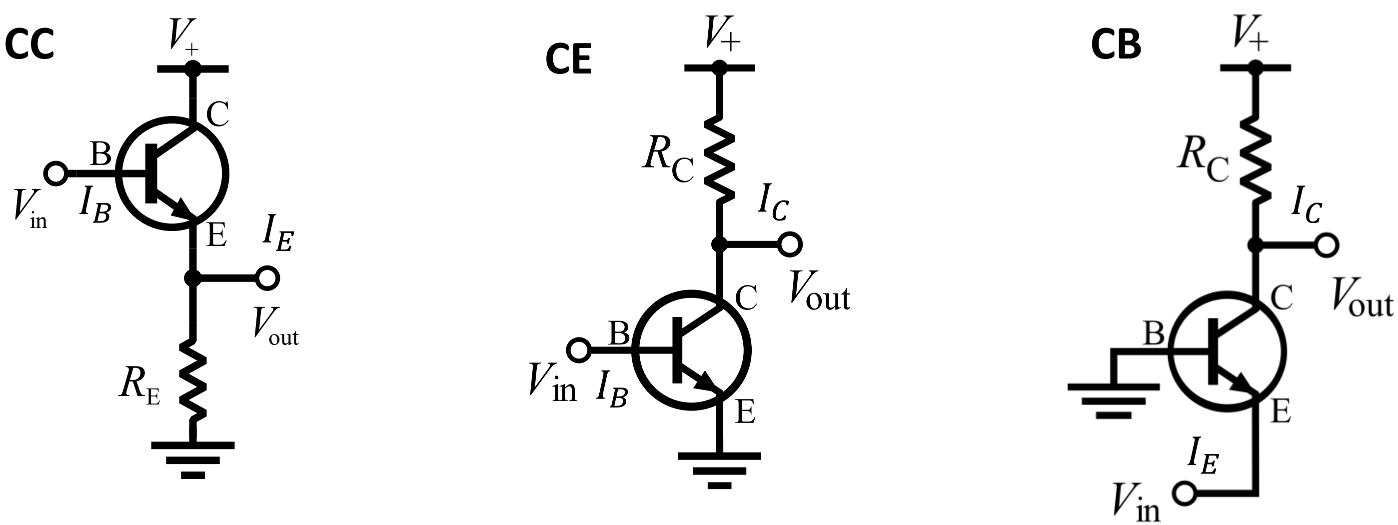
$$V_{BE} = V_B - V_E$$
$$V_{CE} = V_C - V_E$$
$$V_{CB} = V_C - V_B$$
$$I_E = I_C + I_B$$



BJT Configurations

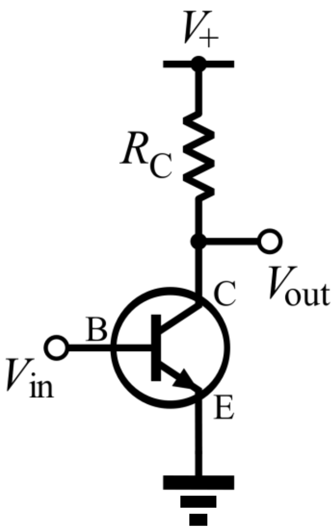
- ❖ As BJT is a **three** terminal device, there are three possible ways to connect it within an electronic circuit with one terminal being **common** to both the **input** and **output**.
- ❖ Each configuration responds differently to its input signal within a circuit.
- ❖ In all configurations, the emitter junction is forward biased and the collector junction is reverse biased.

- **Common Collector (CC) Configuration**
- **Common Emitter (CE) Configuration** ← **frequently used**
- **Common Base (CB) Configuration**

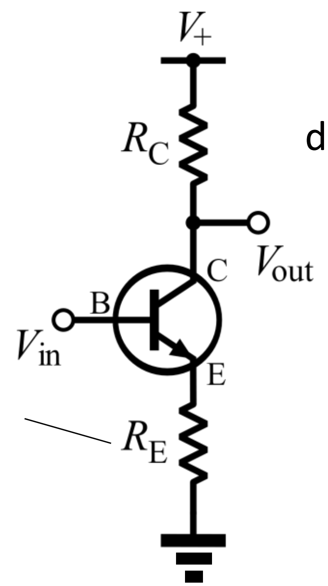


Common Emitter (CE) Configuration

In this configuration, the **base** terminal of the transistor serves as the **input**, the **collector** is the **output**, and the **emitter** is **common** to both (for example, it may be tied to ground reference or a power supply rail). This type of configuration is the most commonly used circuit for transistor-based amplifiers and switches.



A small resister for improving the distortion and stability characteristics of the circuit.

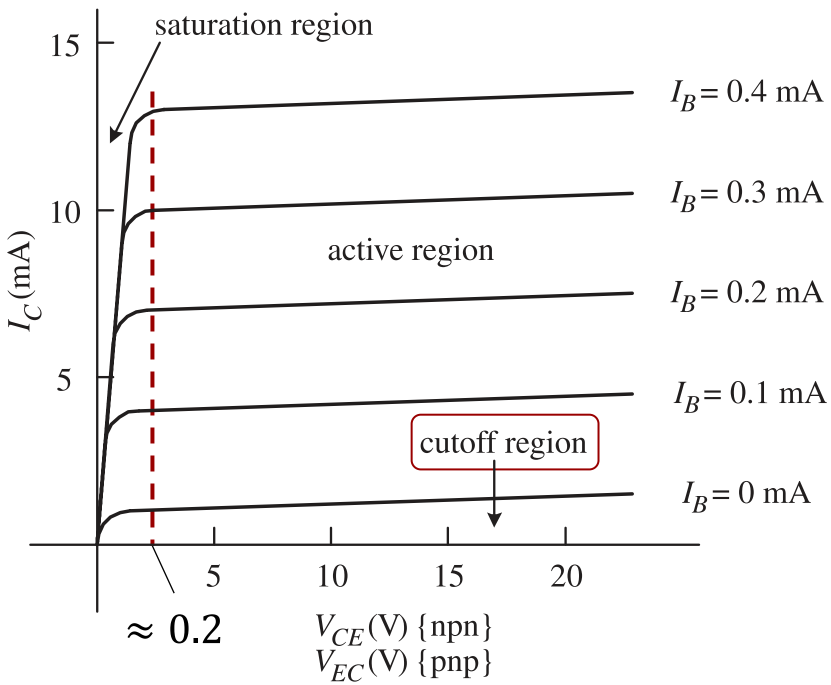


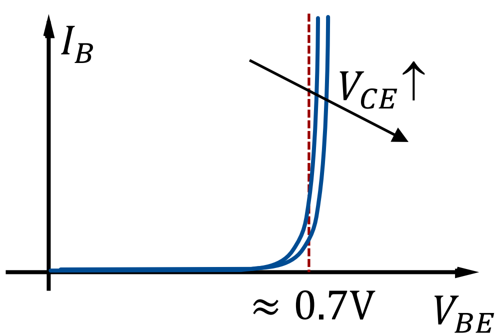
(emitter degeneration)

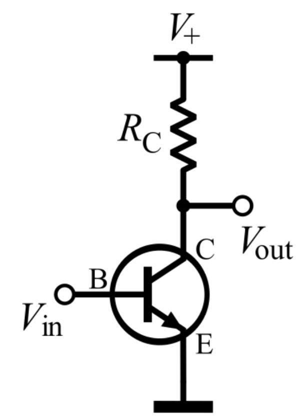
BJT Operation Modes are **Cutoff Mode**, **Saturation Mode**, and **Active Mode**.

BJT Operation Modes: Cutoff Mode

When $V_{BE} < 0.7\text{V}$, and consequently, $I_B = 0$, the transistor acts like an open switch (i.e., transistor is **Fully OFF**) and only a very small **leakage** current (I_C) flows in this mode of operation (Both BE and BC junctions become reverse biased).



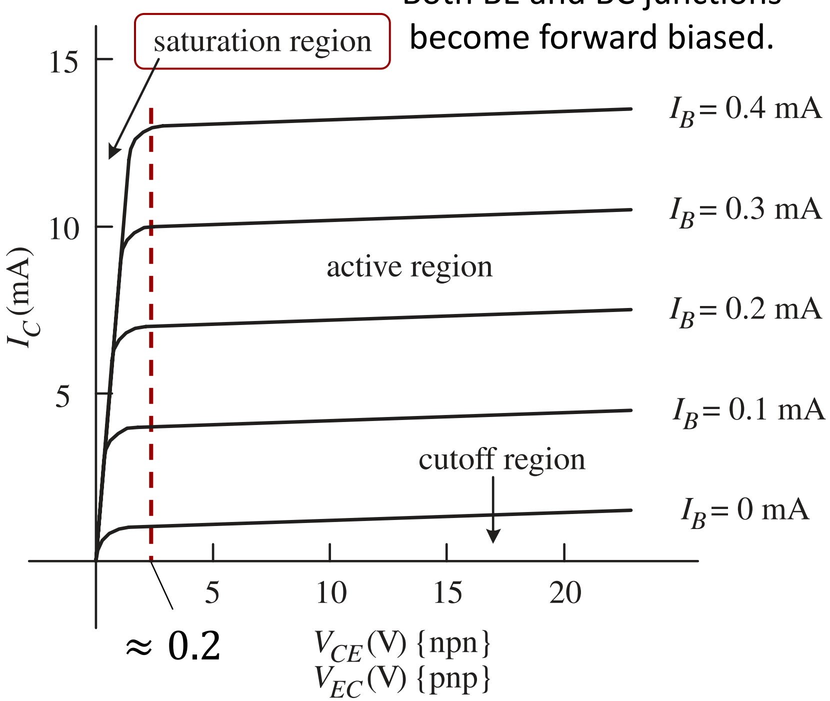




BJT Operation Modes: Saturation Mode

When $V_{BE} \cong 0.7\text{V}$, (and consequently, $I_B > 0$ (sufficiently)) and V_{CE} reaches its minimum ($V_{CE} \leq 0.2$ for a BJT), **maximum** collector current flows to emitter and the transistor acts much like a closed switch (i.e., transistor is **Fully ON**).

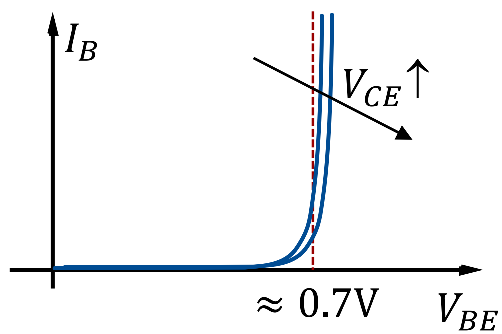
Both BE and BC junctions become forward biased.

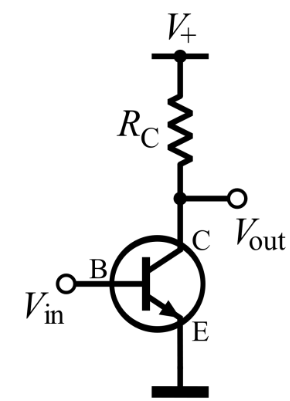


$$I_E = I_C + I_B \qquad I_C \gg \mathrm{I}_B \qquad I_C \neq \beta \mathrm{I}_B$$

I_C is determined by R_C

$$V_{BE} \cong 0.7\ \text{V}$$
$$V_{CE} \cong 0.2\ \text{V}$$





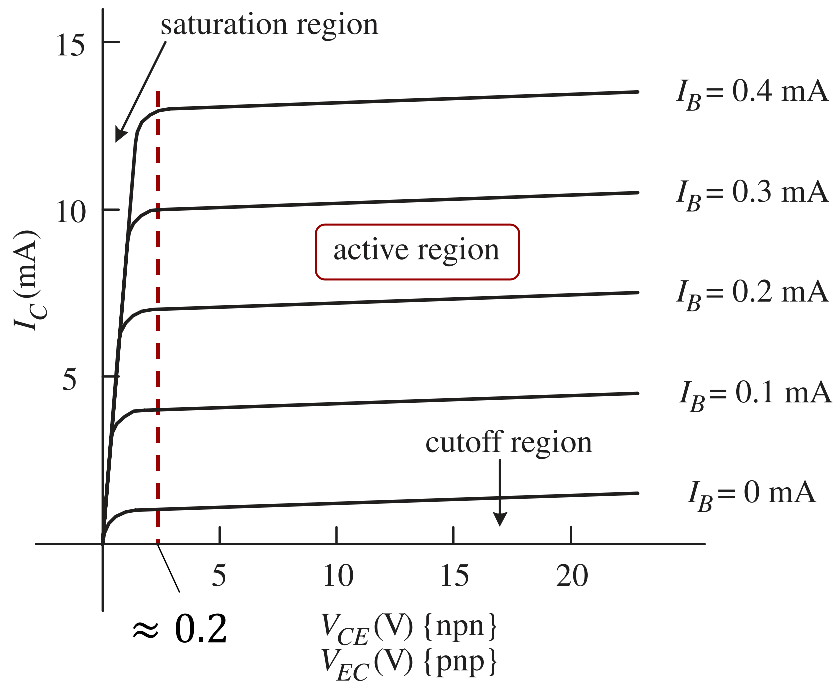
Note: In this mode, power dissipation of BJT is min:

$$P_{\text{BJT}} = I_C V_{CE}$$

Note: In this mode, the I_C is independent of I_B, as long as there is enough I_B to ensure saturation.

BJT Operation Modes: Active Mode

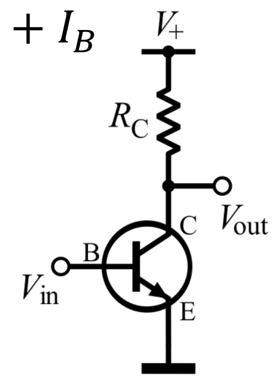
When $V_{BE} \cong 0.7\text{V}$, (and consequently, $I_B > 0$) and $V_{CE} > 0.2$, the transistor acts like an **amplifier** and a nearly-linear relationship exists between terminal currents I_B and I_C.

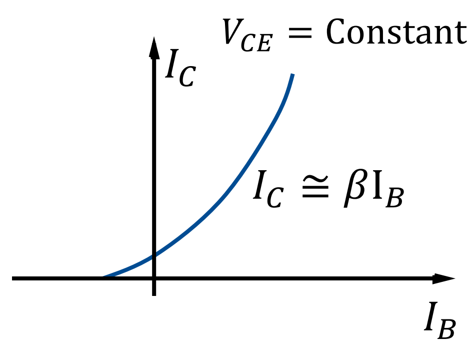


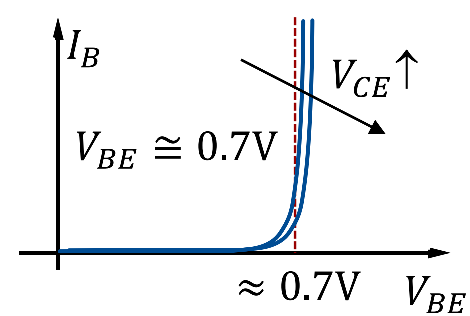
$I_C \cong \beta \mathrm{I}_B$ $\quad I_C \gg \mathrm{I}_B$ $\quad I_E = I_C + I_B$

β is **current gain.**

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$



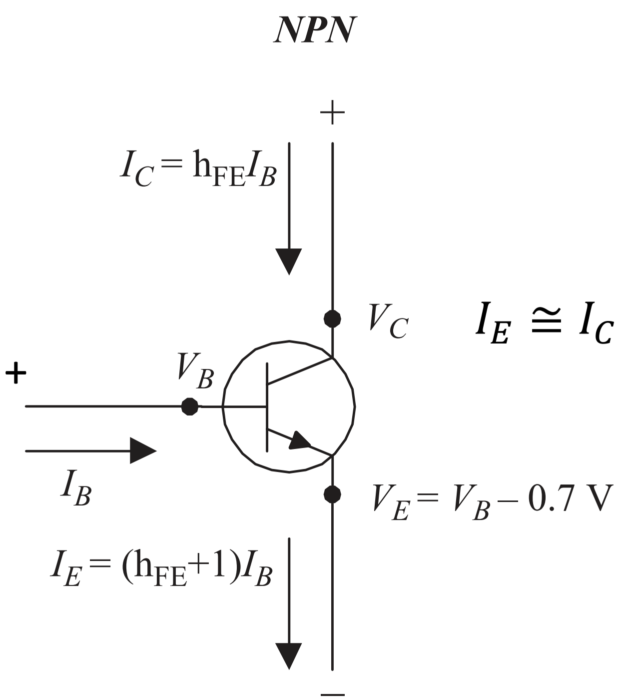


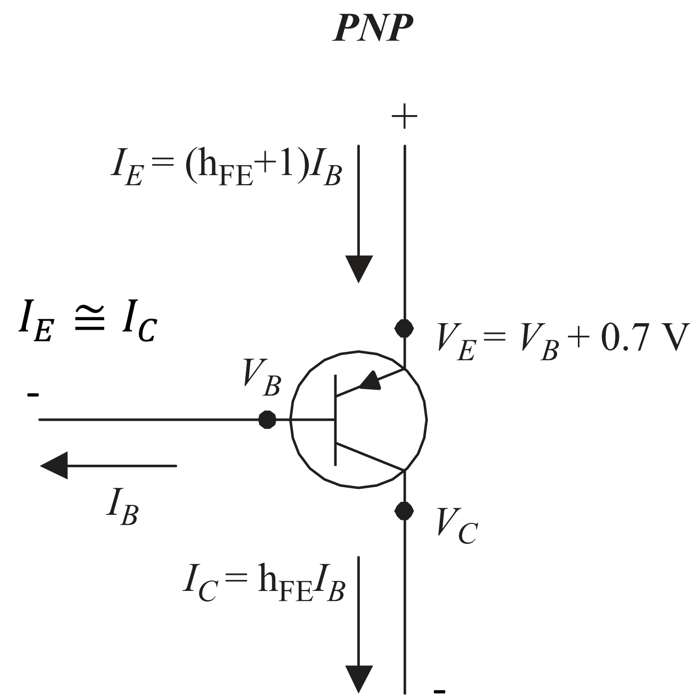


Note: Almost all **power** is dissipated at reverse biased CB junction: $P_{\mathrm{BJT}} = I_C V_{CB} = I_C(V_{CE} - V_{BE})$

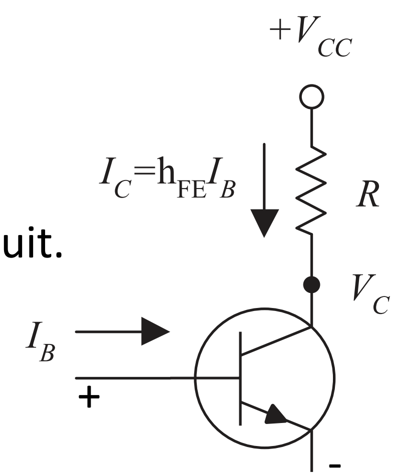
Note: As I_C rises, the voltage drop across R_C increases and V_{CE} drops toward ground.

Voltages & Currents in Active Mode





- V_C depends on the circuit. For example:

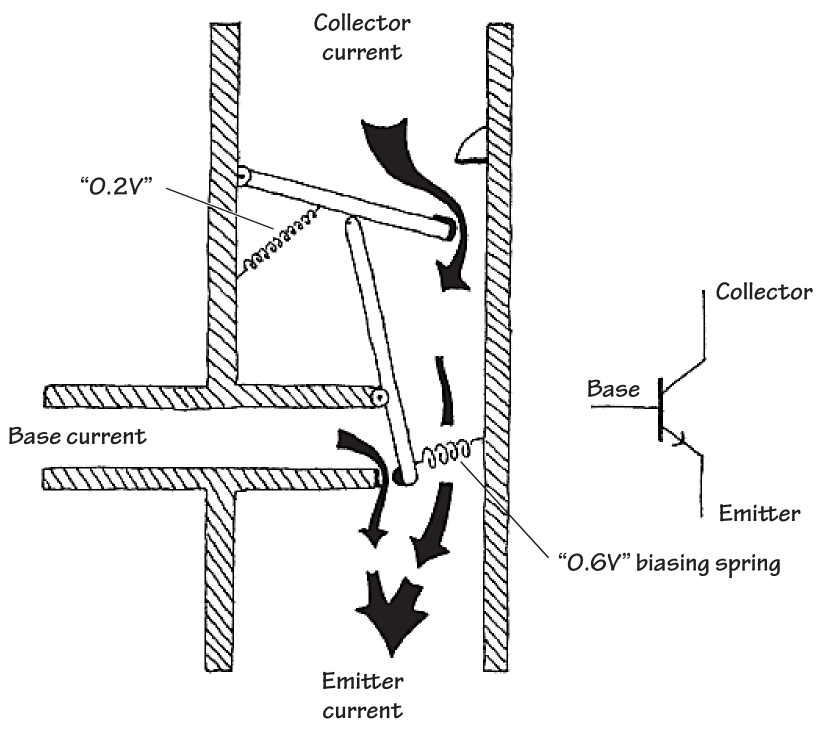


$$V_C = V_{CC} - I_C R$$

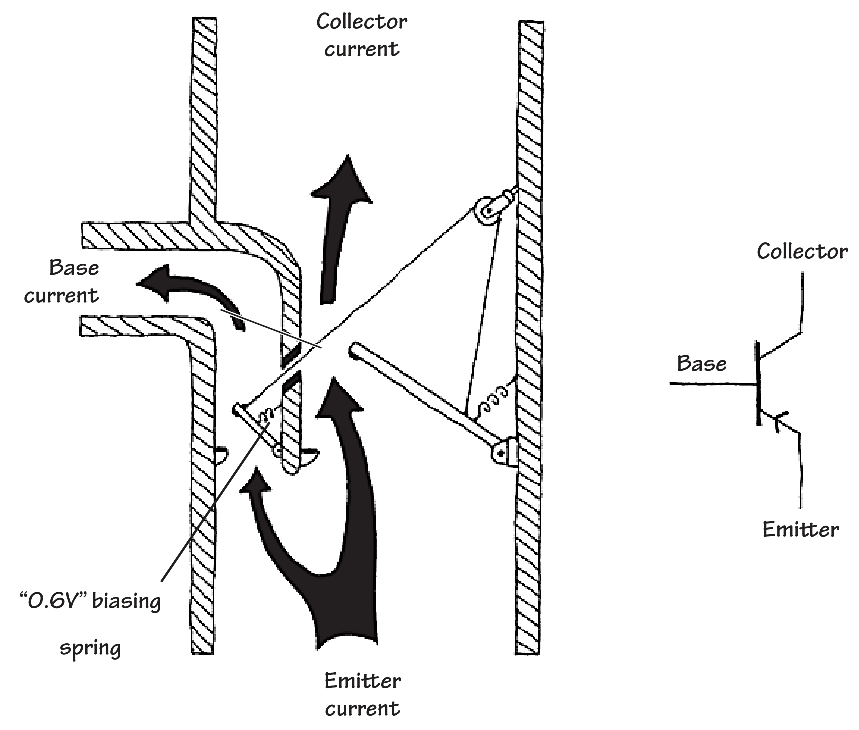
$$V_C = V_{CC} - (h_{FE} I_B) R$$

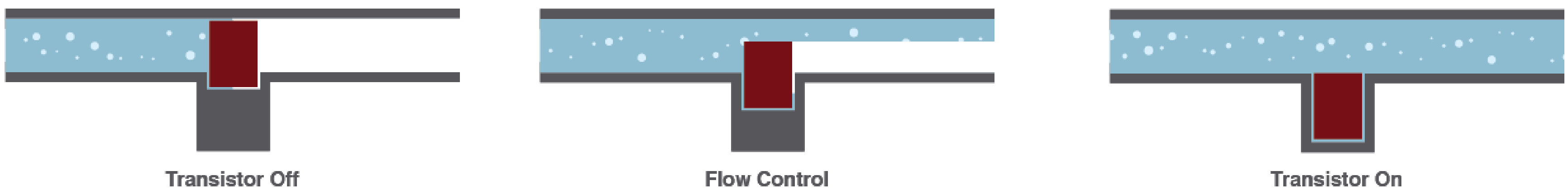
Fluid Analogy

NPN



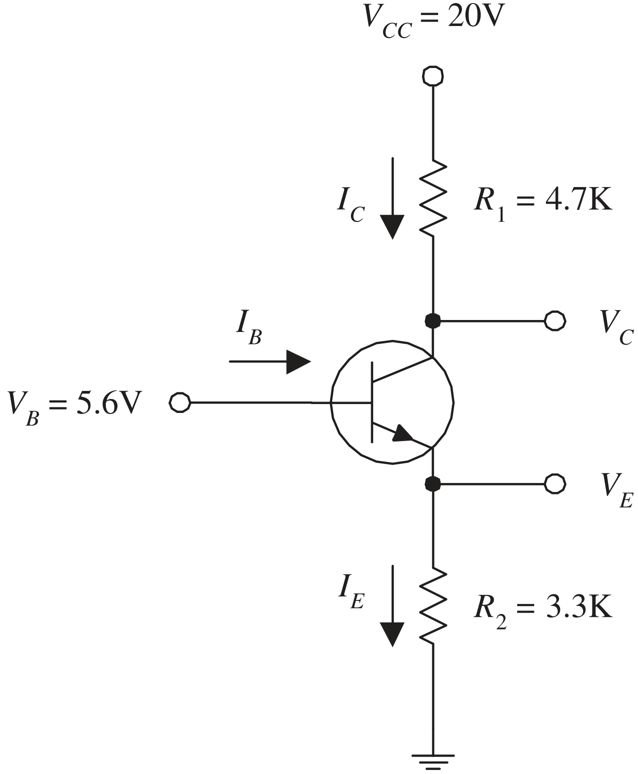
PNP





Example

Assume that the transistor is in Active Mode and $\beta = 100$, find V_E , I_E, I_B, I_C, and V_C ($V_{BE} = 0.6$ V).



Transistor as a Switch

The simplest way to switch moderate to high amounts of power using a low-output current device (e.g., ICs) is to use a transistor. When using a transistor as a **switch** it must be either in **Cutoff Mode** (Fully-OFF) or **Saturation Mode** (Fully-ON). The **Common Emitter** (CE) configuration is more appropriate because it is easy to saturate the transistor.

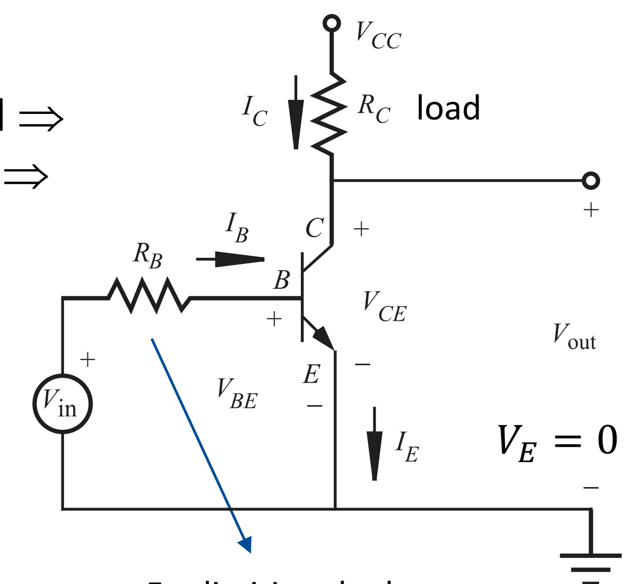
Cutoff or **Fully-OFF Mode:**

$V_{\text{in}} < 0.7\text{V} \Rightarrow V_{BE} < 0.7\text{V} \Rightarrow$ BE junction is reverse biased $\Rightarrow$ $I_B = 0 \Rightarrow I_C = I_E \cong 0$ (leakage) $\Rightarrow V_{\text{out}} = V_{CC}, V_{BE} = V_{\text{in}} \Rightarrow$ open switch.

Saturation or **Fully-ON Mode:**

$V_{\text{in}} > 0.7\text{V}$ (sufficiently) $\Rightarrow V_{BE} \cong 0.7\text{V} \Rightarrow$ BE junction is forward biased $\Rightarrow I_B > 0$ (sufficiently) $\Rightarrow$ BC junction is forward biased $\Rightarrow V_{CE}$ reaches its minimum ($V_{CE} = V_{\text{out}} \leq 0.2\text{V}$ for a BJT) $\Rightarrow$ maximum I_C flows $\Rightarrow$ closed switch.

$$V_{CC} - V_C = R_C I_C$$



For limiting the base current.

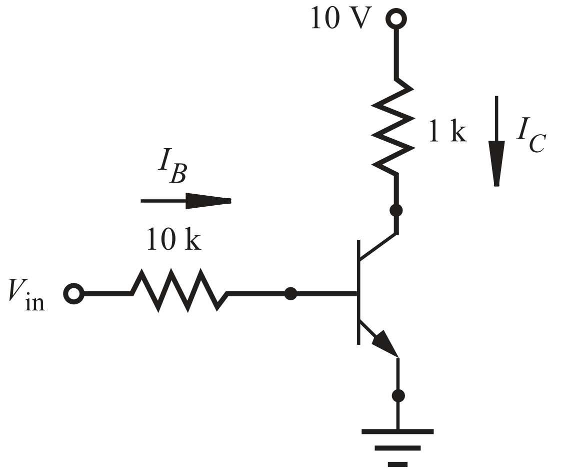
$$I_B = \frac{V_{\text{in}} - V_{BE}}{R_B}$$

Example: Guarantee of Saturation Mode

When designing a transistor switch, we need to guarantee that the transistor is fully saturated when it is on.

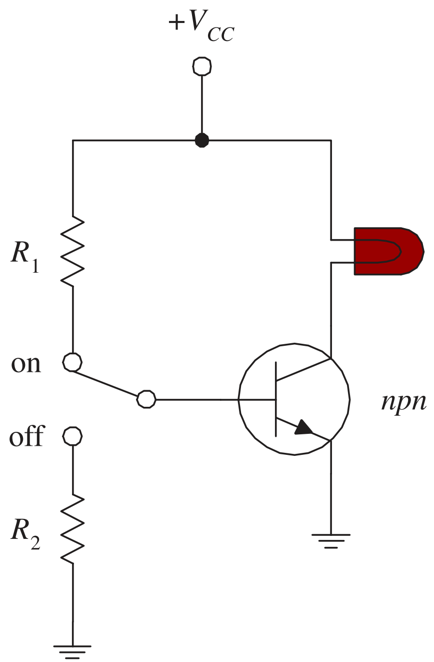
In the following circuit, what **minimum** input voltage V_{in} is necessary to saturate the transistor?

Transistor characteristics:
- Maximum collector current (continuous) = 200 mA
- V_{CE}(sat) = 0.2 V
- V_{BE}(sat) = 0.7 V
- $h_{\text{FE}} = \beta = 100$ (depending on collector current and many other things)

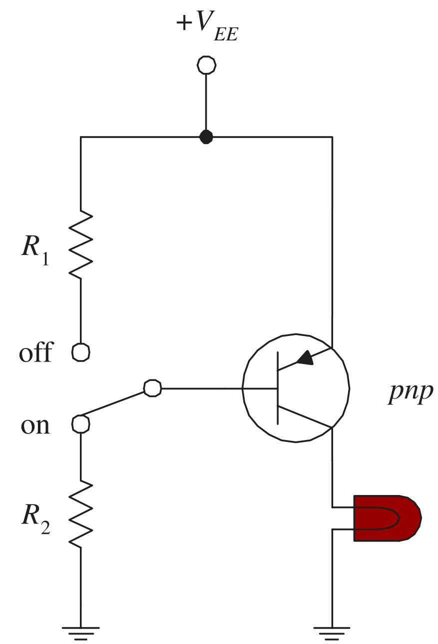


Note: Normally, we use a voltage larger than calculated minimum V_{in} (e.g., 2 to 5 times larger) to ensure that the transistor is fully saturated.

Application: NPN & PNP Transistors as Switch



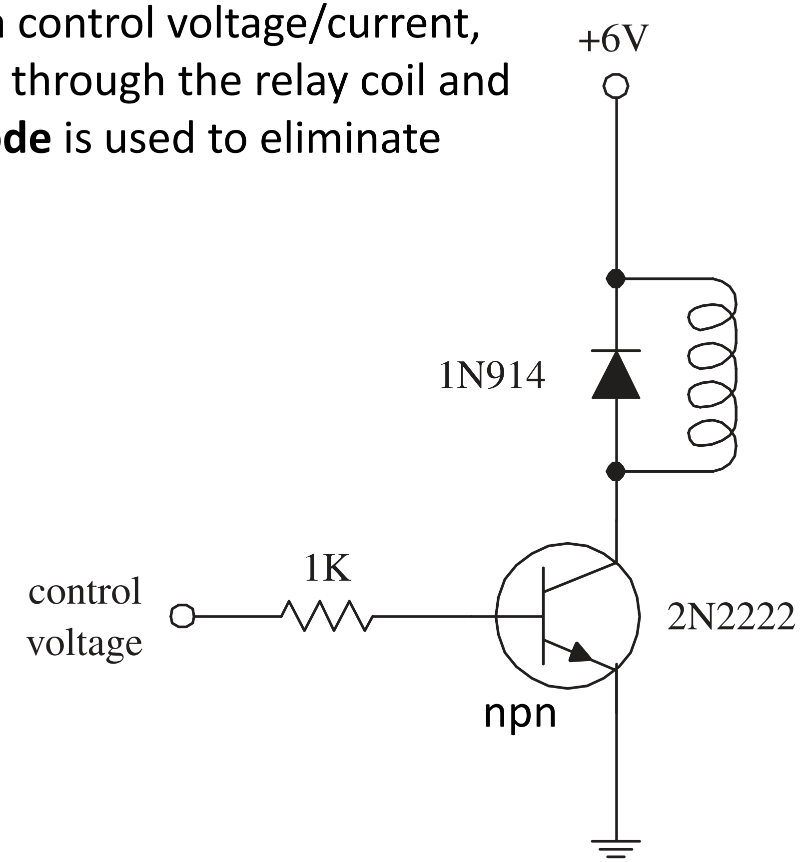
NPN transistor (sinking current)



PNP transistor (sourcing current)

Application: Controlling an Inductive Load

In this circuit, when the transistor's base receives a control voltage/current, the transistor will turn on, allowing current to flow through the relay coil and causing the relay to switch states. The **Fly-Back diode** is used to eliminate voltage spikes created by the relay's coil.

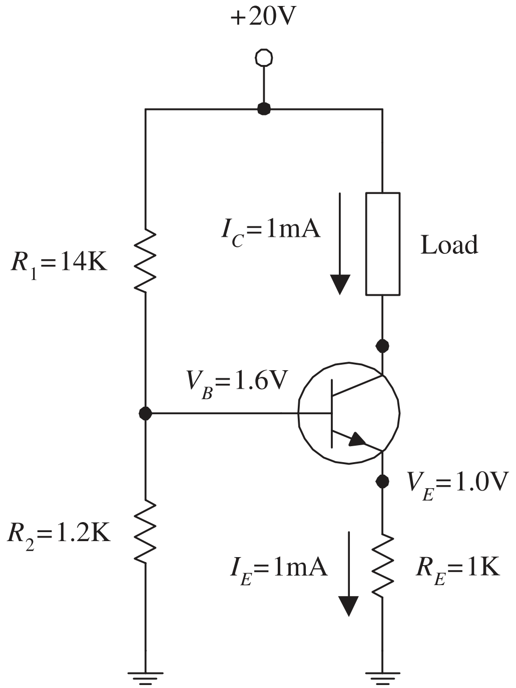


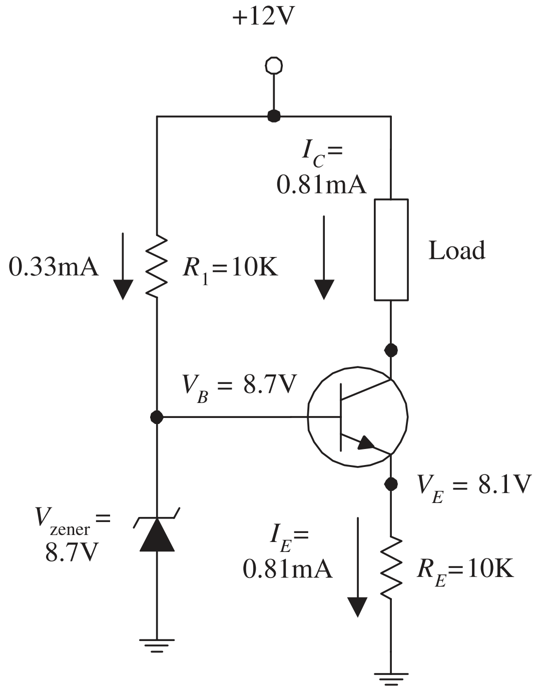
Application: Current Source

Two common methods for biasing a current source are to use either a voltage-divider circuit or a Zener diode regulator.

voltage-divider: $V_B = \dfrac{R_2}{R_1 + R_2} V_{cc}$

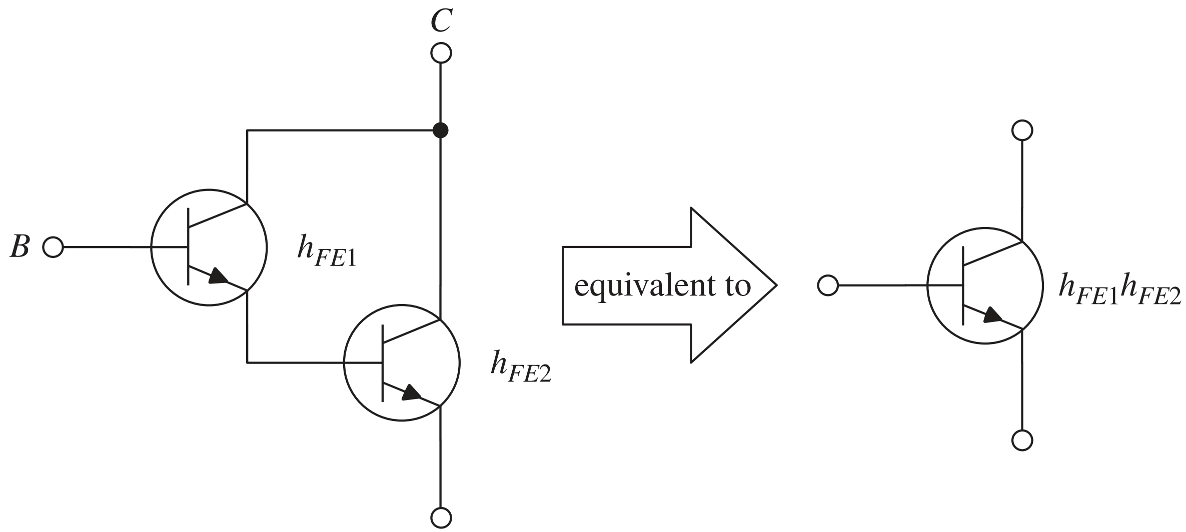
Zener diode regulator: $V_B = V_{\text{zener}}$





Darlington Transistor

By attaching two transistors together, a larger h_{FE} (or β) equivalent transistor circuit, which is equal to the product of the individual transistor's h_{FE} values ($h_{\text{FE}} = h_{\text{FE1}} h_{\text{FE2}}$), is formed.

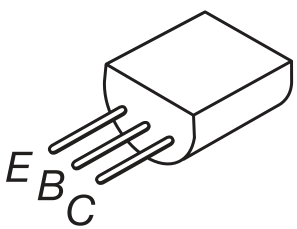


Darlington Pairs usually comes in a single package and they are used for **large current** applications and as input stages for amplifiers, where big input impedances are required. They come in npn (D-npn) and pnp (D-pnp) Darlington packages.

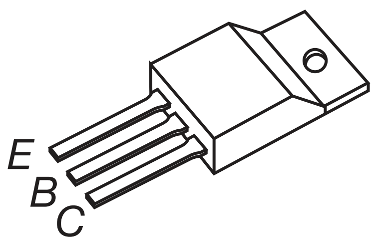
Common BJT Packages

(**TO**: **T**ransistor **O**utline)

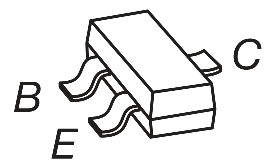
- **TO-92, TO-5, TO-18**: Small-signal transistor package,
- **TO-220**: Power transistor package,
- **TO-3**: High-Power transistor package,
- **SOT-23**: Surface mount transistor package for use on production printed circuit boards (PCBs), but they are less useful for prototyping because of their small size.
- **IC**: A number of transistors combined into a single integrated package.



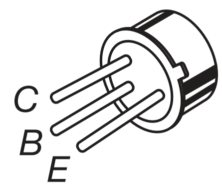
TO-92



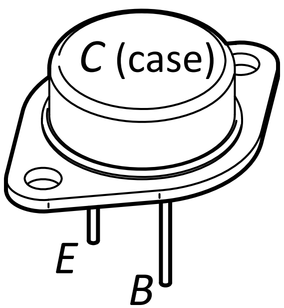
TO-220



SOT-23
(SOT: Small-Outline Transistor)



TO-5
TO-18



TO-3