

Fundamental of Electronics Circuit Design

Chapter 6

Diodes and Transistors

Introduction

- Electronic devices such as diodes, transistors, and
- integrated circuits are made of a semi-conductive material.
- • To understand how these devices work, you should have a basic knowledge of the structure of atoms and the interaction of atomic particles.
- • An important concept introduced in this chapter is that of the *pn* junction that is formed when two different types of semi-conductive material are joined.
- • The *pn* junction is fundamental to the operation of devices such as the solar cell, the diode, and certain types of transistors.

Semiconductors

- is a material that is between conductors and insulators in its ability to conduct electrical current .
- in its pure (intrinsic) state is neither a good conductor nor a good insulator .
- Single-element semiconductors are
 - antimony (Sb), arsenic (As), astatine (At), boron (B), polonium (Po), tellurium (Te), silicon (Si), and germanium (Ge).
 - are characterized by atoms with four valence electrons.
- Compound semiconductors are
 - gallium arsenide, indium phosphide, gallium nitride, silicon carbide, and silicon germanium

Diode and Applications

Basics

- A diode is made from a small piece of semiconductor material, usually silicon, in which half is doped as a p region and half is doped as an n region with a pn junction and depletion region in between.

Allowed to conduct current in one direction while blocking current in the other direction is essential to the operation of many types of circuits.



Diode and operations

- A Diode is an electronic equivalent of a one-way valve; it allows current to flow in only one direction. There are two terminals on a diode, which are known as the anode and cathode. Current is only allowed to flow from anode to cathode.
- The symbol and drawing for the diode are shown in Figure 6.1 and Figure 6.2. The dark band of the diode drawing indicates the cathode mark on the diode symbol. The direction of current flow is indicated by the direction of the triangle. An easy trick for remembering the direction of current flow is to remember that of the current flowing alphabetically, from the anode to the cathode.



Figure 6.1: Circuit symbol for a diode



The unidirectional conduction through a diode is explained by semiconductor physics.

A diode is a junction between N-type and P-type semiconductors, typically fabricated in thin layers as shown in *Figure 6.3*.

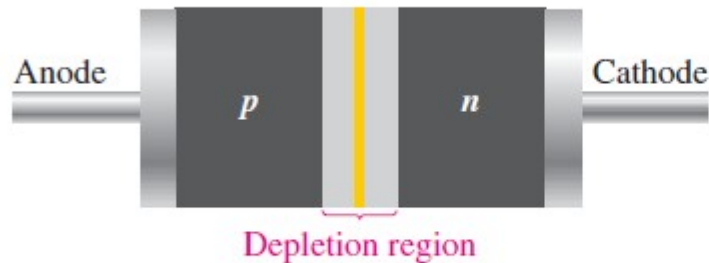
Both N-type and P-type materials are electrically neutral, but have different mechanisms of conduction.

In N-type material, negatively charged electrons are mobile and are the majority current carriers.

In P-type material, positively charged holes are mobile and are the majority current carriers. Holes are actually temporary positive charges created by the lack of an electron;

DIODE OPERATION

- The p region is called the anode and is connected to a conductive terminal. The n region is called the cathode and is connected to a second conductive terminal.



(a) Basic structure



(b) Symbol

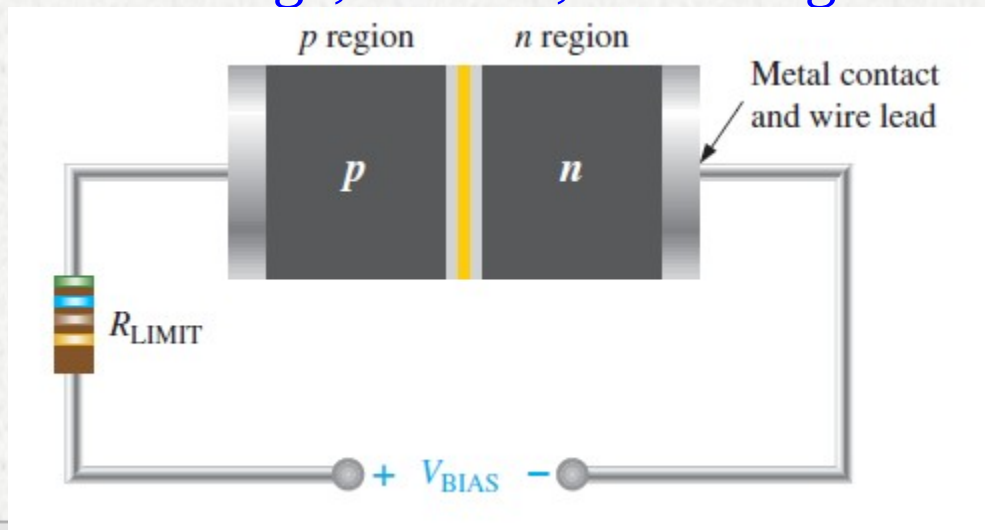
Forward Bias

is the condition that allows current through the pn junction.

The resistor limits the forward current to a value that will not damage the diode.

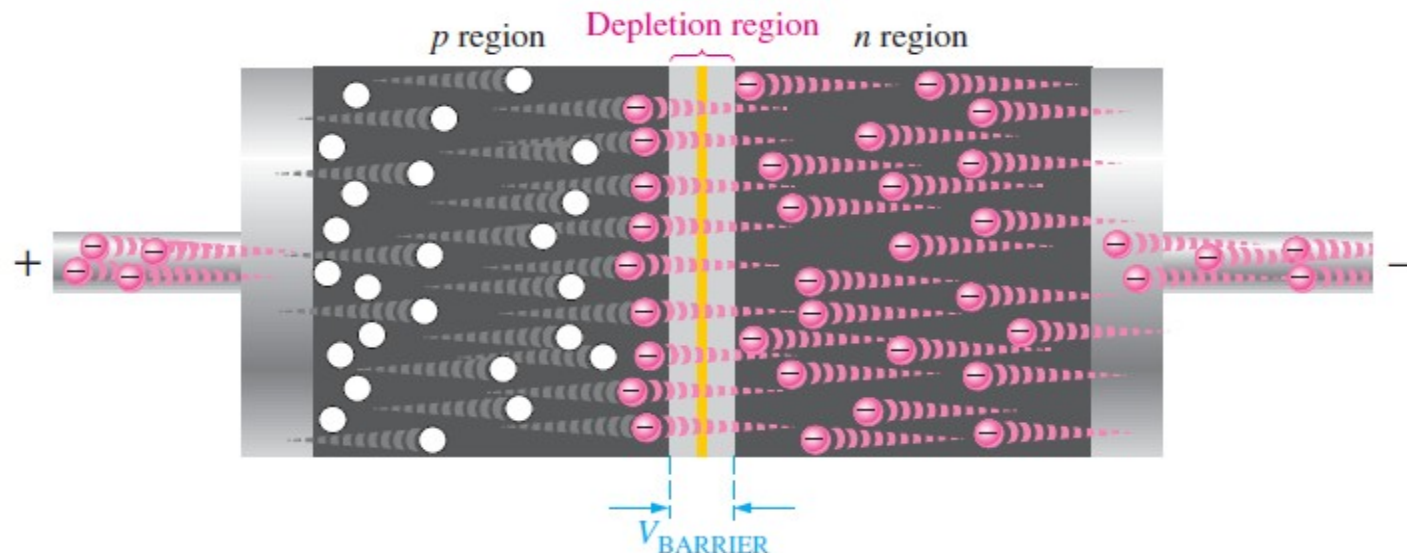
the negative side of V_{BIAS} is connected to the n region of the diode and the positive side is connected to the p region. This is one requirement for forward bias.

the bias voltage, V_{BIAS} , must be greater than the barrier potential.



Forward Bias

Because like charges repel, the negative side of the bias-voltage source “pushes” the free electrons, which are the majority carriers in the n region, toward the pn junction. This flow of free electrons is called electron current. The negative side of the source also provides a continuous flow of electrons through the external connection (conductor) and into the n region as shown.

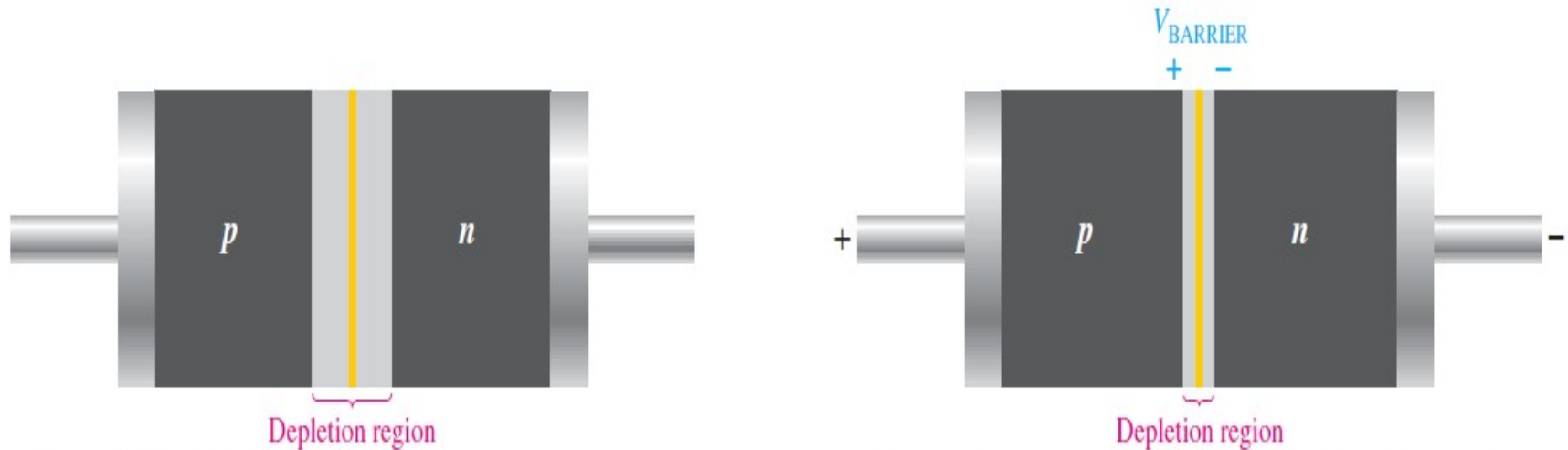


Forward Bias

- The bias-voltage source imparts sufficient energy to the free electrons for them to overcome the barrier potential of the depletion region and move on through into the p region. Once in the p region, these conduction electrons have lost enough energy to immediately combine with holes in the valence band.
- Now, the electrons are in the valence band in the p region, simply because they have lost too much energy overcoming the barrier potential to remain in the conduction band.

The Effect of Forward Bias on the Depletion Region

- Forward bias causes the depletion region to narrow.



(a) At equilibrium (no bias)

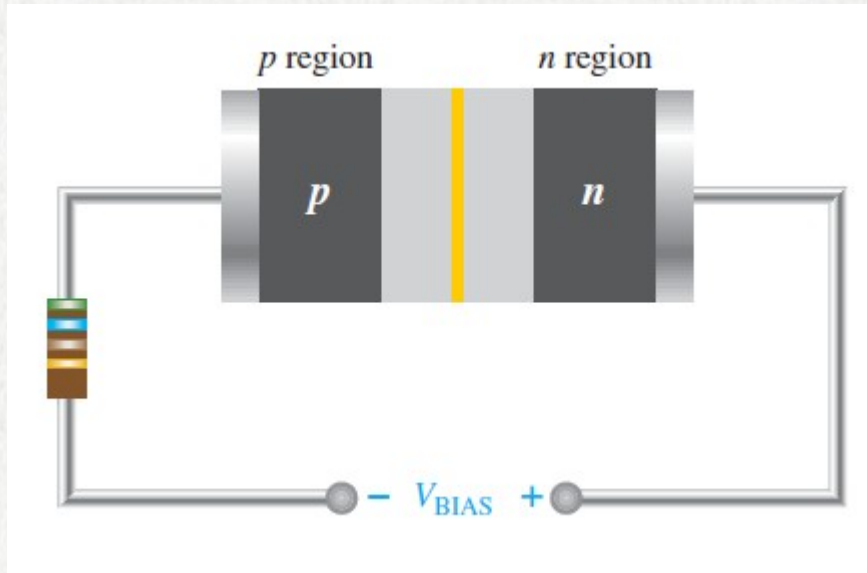
(b) Forward bias narrows the depletion region and produces a voltage drop across the pn junction equal to the barrier potential.

The Effect of the Barrier Potential During Forward Bias

- When forward bias is applied, the free electrons are provided with enough energy from the bias-voltage source to overcome the barrier potential and effectively “climb the energy hill” and cross the depletion region.
- The energy that the electrons require in order to pass through the depletion region is equal to the barrier potential.
- An additional small voltage drop occurs across the p and n regions due to the internal resistance of the material.

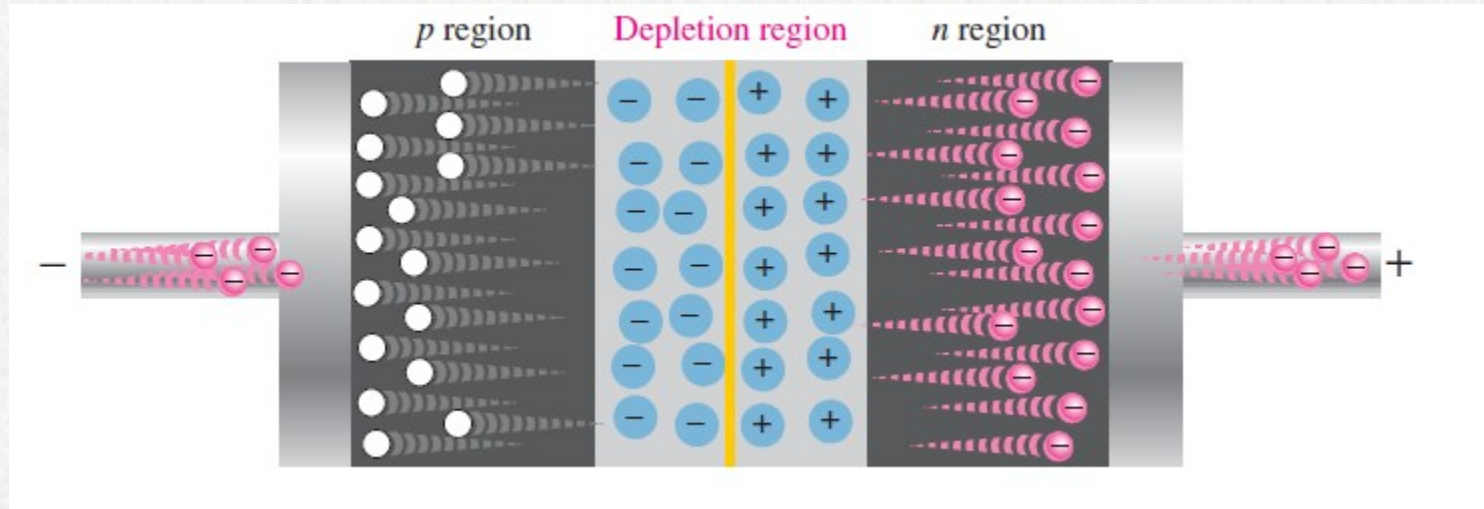
Reverse Bias

- is the condition that essentially prevents current through the diode.
- the positive side of V_{BIAS} is connected to the n region of the diode and the negative side is connected to the p region.



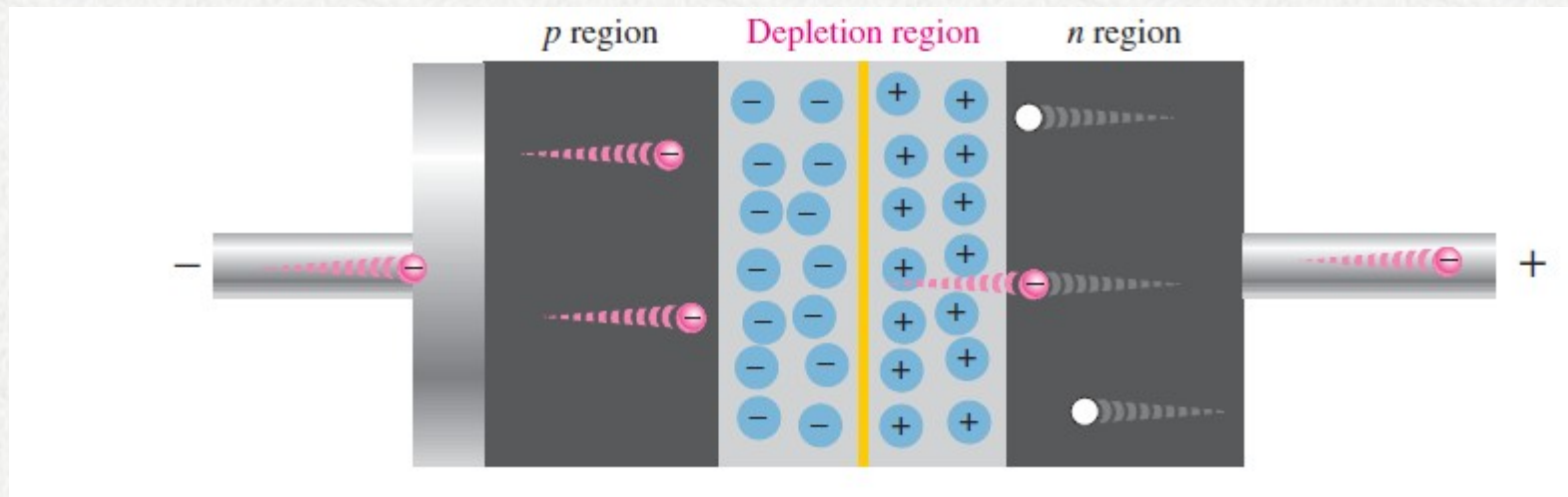
The Effect of Reverse bias on the Depletion Region

- Reverse bias causes the depletion region to narrow.



Reverse Current

- The extremely small current that exists in reverse bias after the transition current dies out is caused by the minority carriers in the n and p regions that are produced by thermally generated electron-hole pairs.

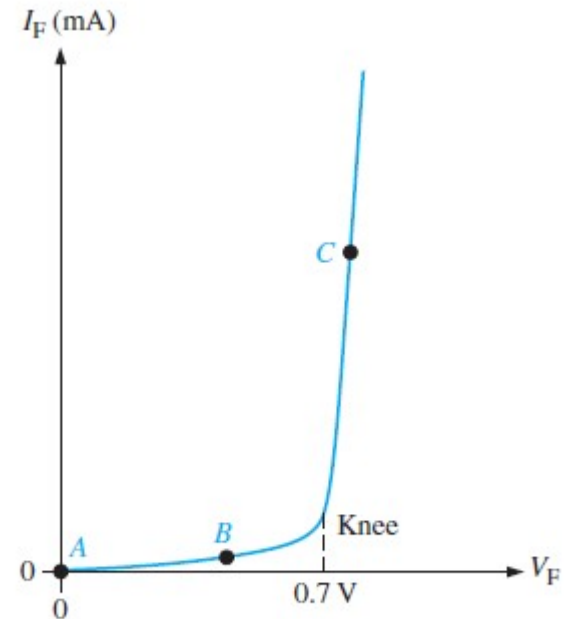


Reverse Breakdown

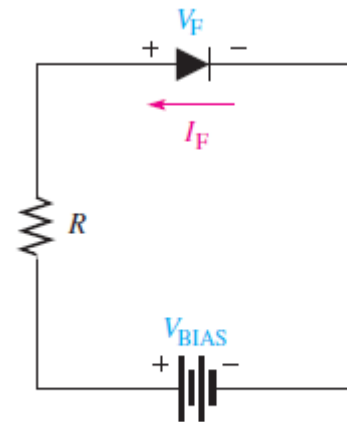
- if the external reverse-bias voltage is increased to a value called the breakdown voltage, the reverse current will drastically increase.
- The multiplication of conduction electrons is known as the avalanche effect, and reverse current can increase dramatically if steps are not taken to limit the current.

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.



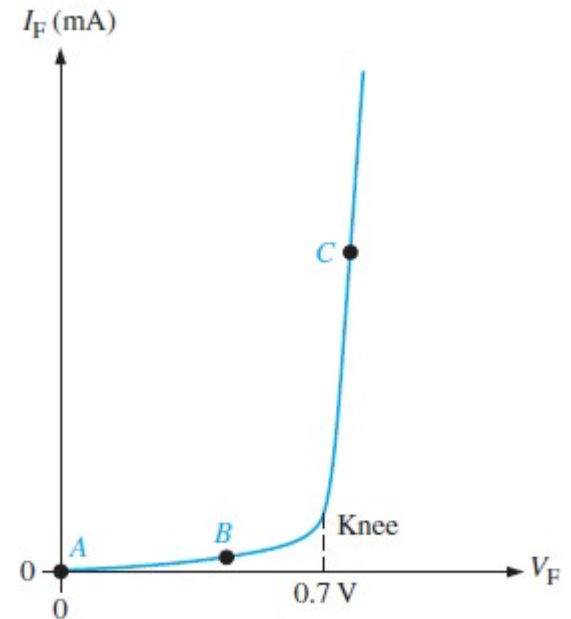
(a) V-I characteristic curve for forward bias.



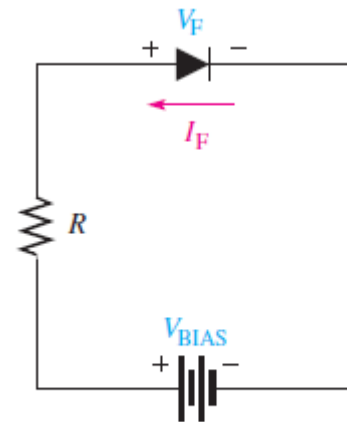
(a) Forward bias

VI Characteristic for forward bias.

- the forward current increases very little until the forward voltage across the pn junction reaches approximately 0.7 V at the knee of the curve.
- After this point, the forward voltage remains nearly constant at approximately 0.7 V, but I_F increases rapidly.



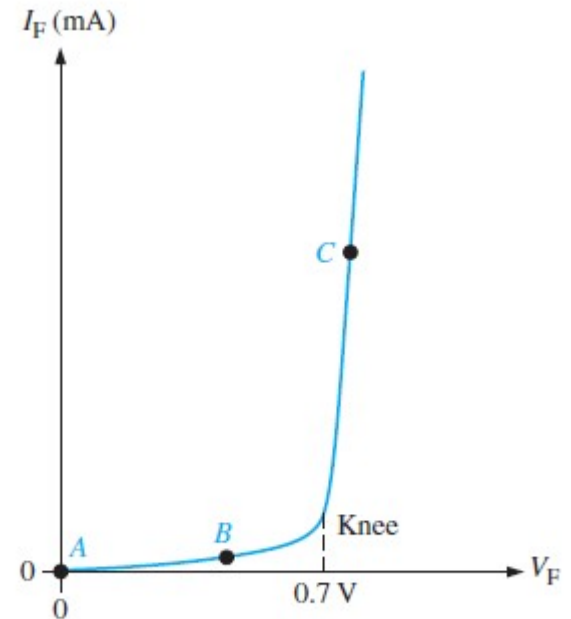
(a) V - I characteristic curve for forward bias.



(a) Forward bias

Dynamic Resistance

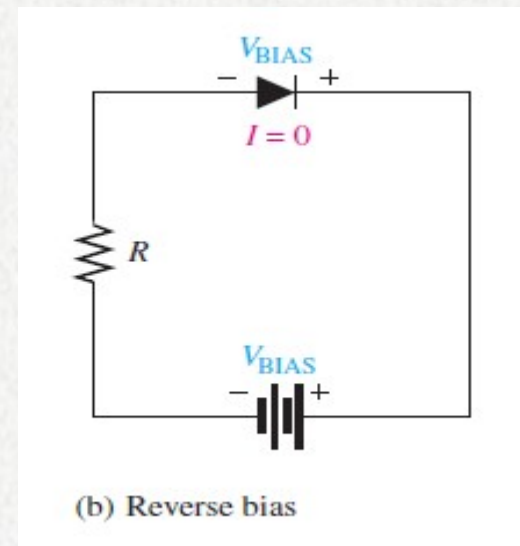
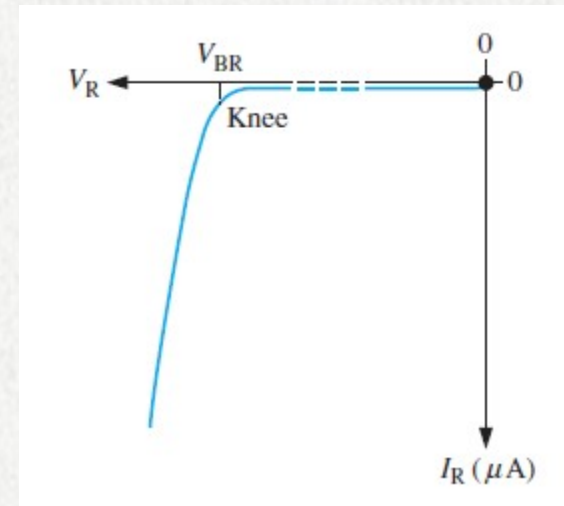
- The resistance of the forward-biased diode is not constant over the entire curve.
- Because the resistance changes as you move along the V-I curve, it is called dynamic or ac resistance.
- Below the knee of the curve the resistance is greatest because the current increases very little for a given change in voltage
- The resistance begins to decrease in the region of the knee of the curve and becomes smallest above the knee where there is a large change in current for a given change in voltage.



(a) V-I characteristic curve for forward bias.

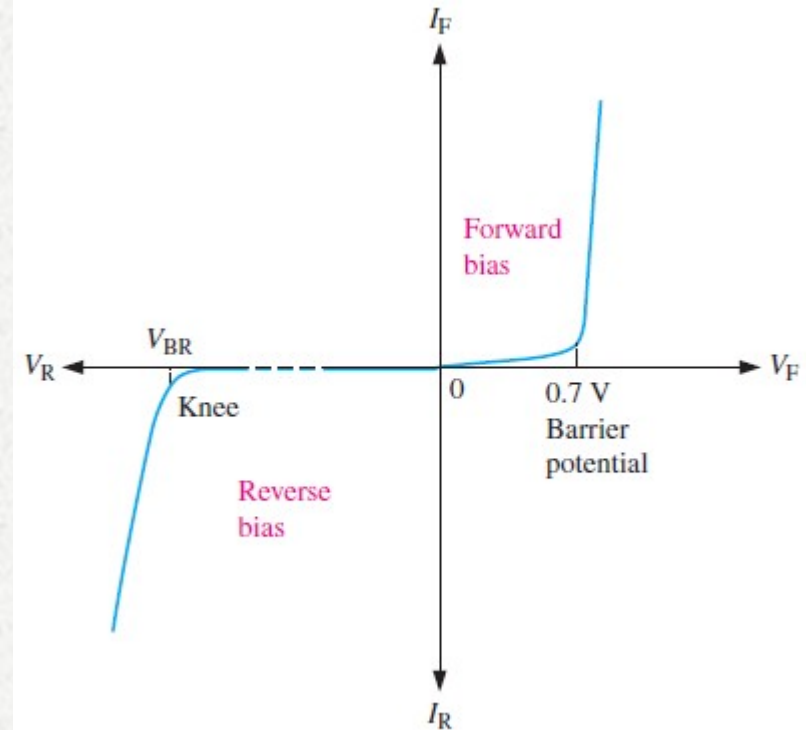
V-I Characteristic for Reverse Bias.

- 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.



The Complete V-I Characteristic Curve

- Combine the curves for both forward bias and reverse bias, and you have the complete V-I characteristic curve for a diode, as shown in the figure.

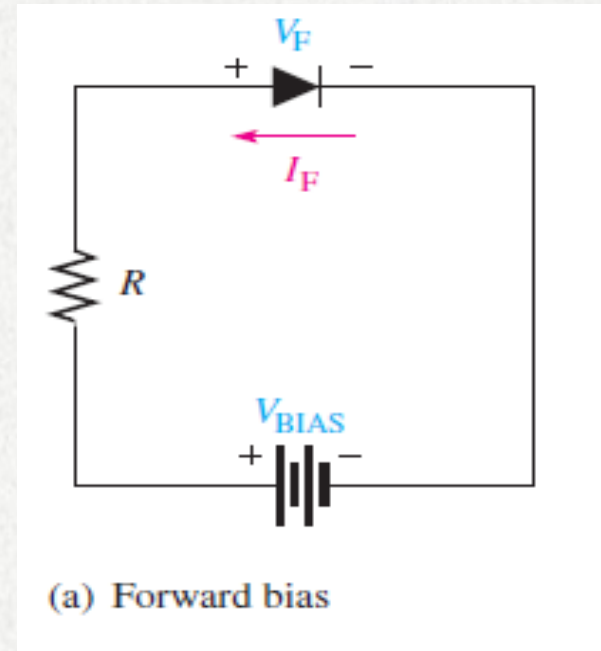


DIODE MODELS

Bias Connections

• *Forward-Bias*

- The positive terminal of the source is connected to the anode through a current-limiting resistor.
- The negative terminal of the source is connected to the cathode.
- The forward current (I_F) is from cathode to anode as indicated.
- The forward voltage drop (V_F) due to the barrier potential is from positive at the anode to negative at the cathode.

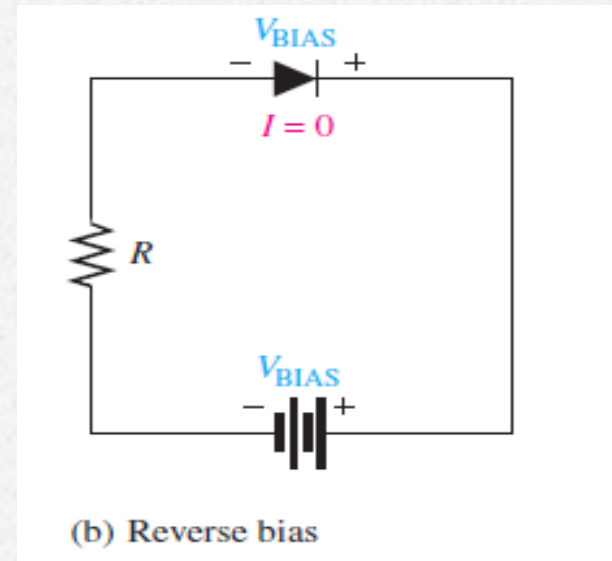


DIODE MODELS

Bias Connections

- **Reverse-Bias**

- The negative terminal of the source is connected to the anode side of the circuit, and the positive terminal is connected to the cathode side.
- A resistor is not necessary in reverse bias but it is shown for circuit consistency.
- The reverse current is extremely small and can be considered to be zero.

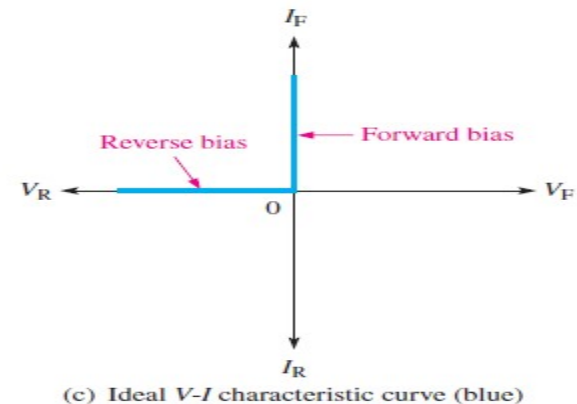
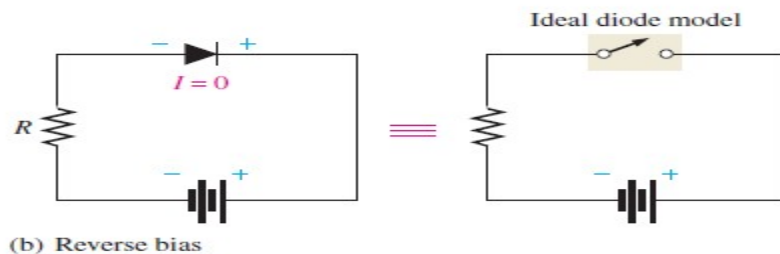
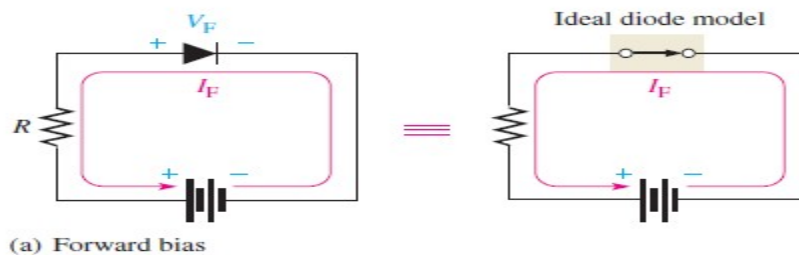


DIODE MODELS

Diode Approximations

The Ideal Diode Model

- is the least accurate approximation and can be represented by a simple switch.
- Although the barrier potential, the forward dynamic resistance, and the reverse current are all neglected, this model is adequate for most troubleshooting when you are trying to determine if the diode is working properly.

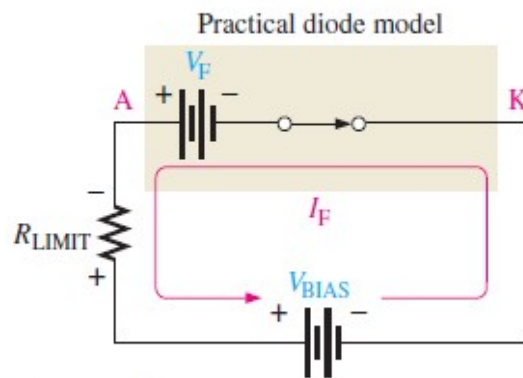


DIODE MODELS

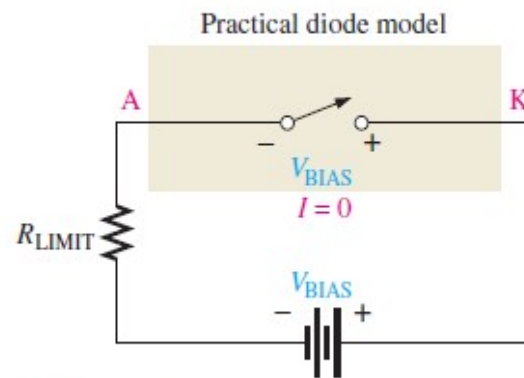
Diode Approximations

The Practical Diode Model

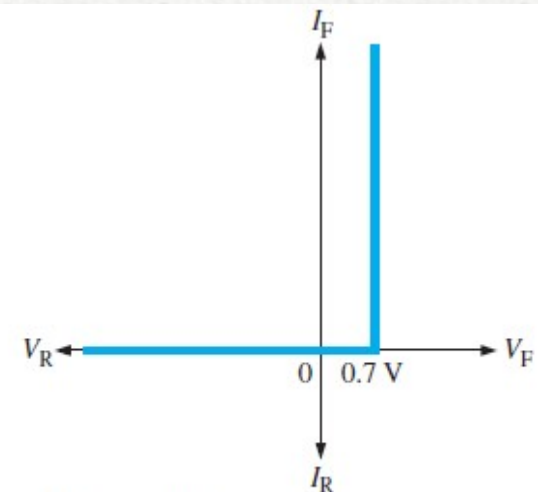
- The practical model includes the barrier potential, the dynamic resistance is neglected,
- When the diode is forward-biased, it is equivalent to a closed switch in series with a small equivalent voltage source (V_F) equal to the barrier potential (0.7 V) with the positive side toward the anode,



(a) Forward bias



(b) Reverse bias



(c) Characteristic curve (silicon)

DIODE MODELS

Diode Approximations

The Practical Diode Model

- When the diode is reverse-biased, it is equivalent to an open switch just as in the ideal model, The barrier potential does not affect reverse bias, so it is not a factor.
- The diode is assumed to have zero reverse current, as indicated by the portion of the curve on the negative horizontal axis.
- useful when you are troubleshooting in lower-voltage circuits.
- useful when you are designing basic diode circuits.

DIODE MODELS

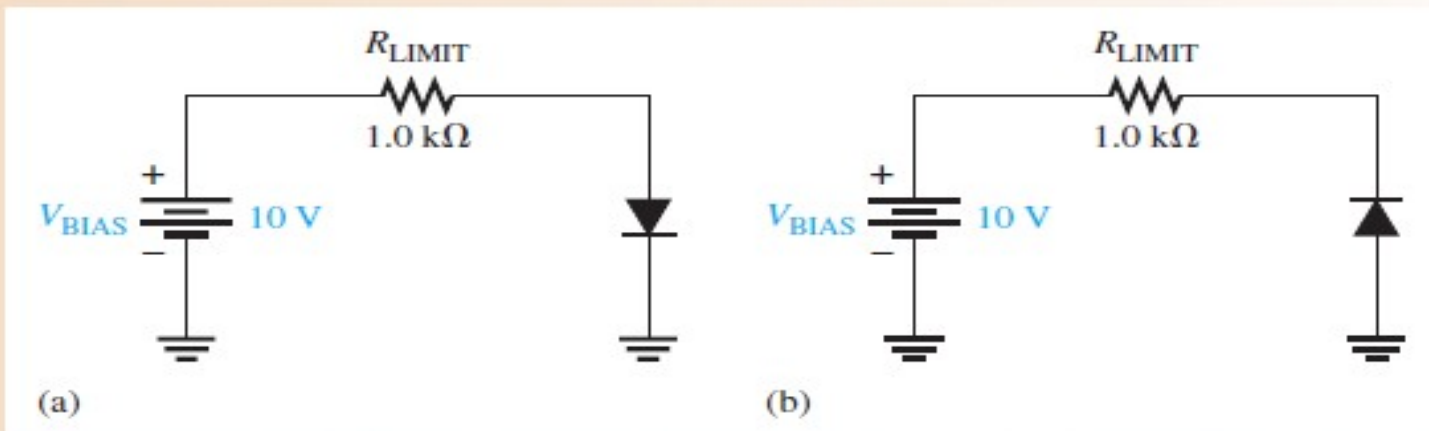
Diode Approximations

The Complete Diode Model

- is the most accurate approximation and includes the barrier potential, the small forward dynamic resistance and the large internal reverse resistance
- The reverse resistance is taken into account because it provides a path for the reverse current, which is included in this diode model.
- When the diode is forward-biased, it acts as a closed switch in series with the equivalent barrier potential voltage (V_B) and the small forward dynamic resistance
- When the diode is reverse-biased, it acts as an open switch in parallel with the large internal reverse resistance. The barrier potential does not affect reverse bias, so it is not a factor.

EXAMPLE

- (a) Determine the forward voltage and forward current for the diode in Figure 2–18(a) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $r'_d = 10\ \Omega$ at the determined value of forward current.
- (b) Determine the reverse voltage and reverse current for the diode in Figure 2–18(b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $I_R = 1\ \mu\text{A}$.



▲ FIGURE 2–18

Solution

(a) Ideal model:

$$V_F = 0 \text{ V}$$

$$I_F = \frac{V_{\text{BIAS}}}{R_{\text{LIMIT}}} = \frac{10 \text{ V}}{1.0 \text{ k}\Omega} = 10 \text{ mA}$$

$$V_{R_{\text{LIMIT}}} = I_F R_{\text{LIMIT}} = (10 \text{ mA})(1.0 \text{ k}\Omega) = 10 \text{ V}$$

Practical model:

$$V_F = 0.7 \text{ V}$$

$$I_F = \frac{V_{\text{BIAS}} - V_F}{R_{\text{LIMIT}}} = \frac{10 \text{ V} - 0.7 \text{ V}}{1.0 \text{ k}\Omega} = \frac{9.3 \text{ V}}{1.0 \text{ k}\Omega} = 9.3 \text{ mA}$$

$$V_{R_{\text{LIMIT}}} = I_F R_{\text{LIMIT}} = (9.3 \text{ mA})(1.0 \text{ k}\Omega) = 9.3 \text{ V}$$

Complete model:

$$I_F = \frac{V_{\text{BIAS}} - 0.7 \text{ V}}{R_{\text{LIMIT}} + r'_d} = \frac{10 \text{ V} - 0.7 \text{ V}}{1.0 \text{ k}\Omega + 10 \Omega} = \frac{9.3 \text{ V}}{1010 \Omega} = 9.21 \text{ mA}$$

$$V_F = 0.7 \text{ V} + I_F r'_d = 0.7 \text{ V} + (9.21 \text{ mA})(10 \Omega) = 792 \text{ mV}$$

$$V_{R_{\text{LIMIT}}} = I_F R_{\text{LIMIT}} = (9.21 \text{ mA})(1.0 \text{ k}\Omega) = 9.21 \text{ V}$$

Solution

(b) Ideal model:

$$\begin{aligned}I_R &= 0 \text{ A} \\V_R &= V_{\text{BIAS}} = 10 \text{ V} \\V_{R_{\text{LIMIT}}} &= 0 \text{ V}\end{aligned}$$

Practical model:

$$\begin{aligned}I_R &= 0 \text{ A} \\V_R &= V_{\text{BIAS}} = 10 \text{ V} \\V_{R_{\text{LIMIT}}} &= 0 \text{ V}\end{aligned}$$

Complete model:

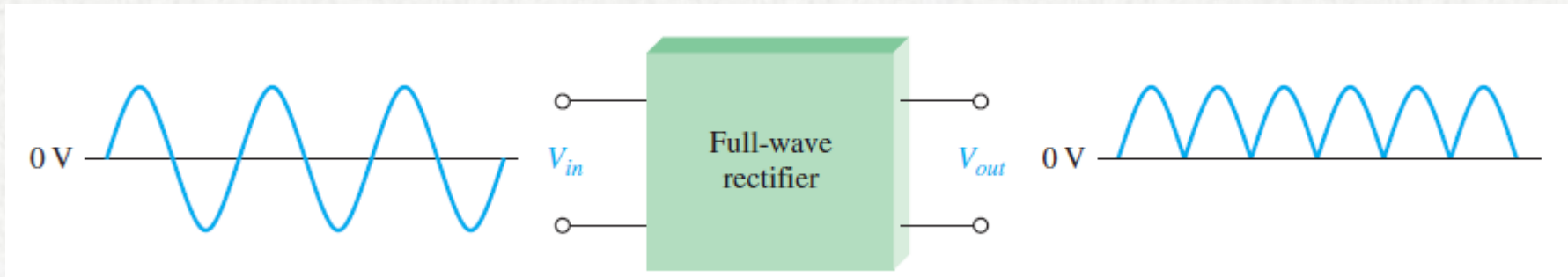
$$\begin{aligned}I_R &= 1 \mu\text{A} \\V_{R_{\text{LIMIT}}} &= I_R R_{\text{LIMIT}} = (1 \mu\text{A})(1.0 \text{ k}\Omega) = 1 \text{ mV} \\V_R &= V_{\text{BIAS}} - V_{R_{\text{LIMIT}}} = 10 \text{ V} - 1 \text{ mV} = 9.999 \text{ V}\end{aligned}$$

HALF-WAVE RECTIFIERS

- Because of their ability to conduct current in one direction and block current in the other direction, diodes are used in circuits called rectifiers that convert ac voltage into dc voltage.
- Rectifiers are found in all dc power supplies that operate from an ac voltage source.

FULL-WAVE RECTIFIERS

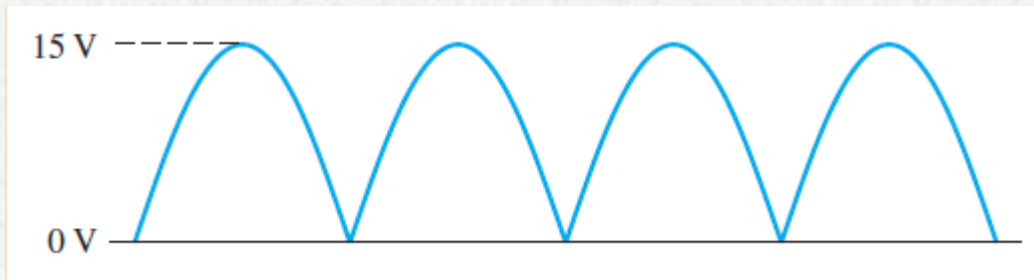
- The most commonly used type in dc power supplies.
- Allows unidirectional (one-way) current through the load during the entire 360 of the input cycle,
- The result of full-wave rectification is an output voltage with a frequency twice the input frequency and that pulsates every half-cycle of the input



- The number of positive alternations that make up the full-wave rectified voltage is twice that of the half-wave voltage for the same time interval.
- The average value, which is the value measured on a dc voltmeter, for a full-wave rectified sinusoidal voltage is twice that of the half-wave, as shown in the following formula:
$$V_{AVG} = \frac{2V_p}{\pi}$$
- V_{AVG} is approximately 63.7% of V_p for a full-wave rectified voltage.

Example

- Find the average value of the full-wave rectified voltage in Figure below.



- Solution

$$V_{\text{AVG}} = \frac{2V_p}{\pi} = \frac{2(15 \text{ V})}{\pi} = \mathbf{9.55 \text{ V}}$$

V_{AVG} is 63.7% of V_p .

Solution

Solution The transformer turns ratio is $n = 0.1$. The peak primary voltage is

$$V_{p(pri)} = 1.414V_{rms} = 1.414(120 \text{ V}) = 170 \text{ V}$$

The peak secondary voltage is

$$V_{p(sec)} = nV_{p(pri)} = 0.1(170 \text{ V}) = 17.0 \text{ V}$$

The unfiltered peak full-wave rectified voltage is

$$V_{p(rect)} = V_{p(sec)} - 1.4 \text{ V} = 17.0 \text{ V} - 1.4 \text{ V} = 15.6 \text{ V}$$

The frequency of a full-wave rectified voltage is 120 Hz. The approximate peak-to-peak ripple voltage at the output is

$$V_{r(pp)} \cong \left(\frac{1}{fR_L C} \right) V_{p(rect)} = \left(\frac{1}{(120 \text{ Hz})(220 \Omega)(1000 \mu\text{F})} \right) 15.6 \text{ V} = 0.591 \text{ V}$$

The approximate dc value of the output voltage is determined as follows:

$$V_{DC} = \left(1 - \frac{1}{2fR_L C} \right) V_{p(rect)} = \left(1 - \frac{1}{(240 \text{ Hz})(220 \Omega)(1000 \mu\text{F})} \right) 15.6 \text{ V} = 15.3 \text{ V}$$

The resulting ripple factor is

$$r = \frac{V_{r(pp)}}{V_{DC}} = \frac{0.591 \text{ V}}{15.3 \text{ V}} = \mathbf{0.039}$$

The percent ripple is 3.9%.

Voltage Regulators

- While filters can reduce the ripple from power supplies to a low value, the most effective approach is a combination of a capacitor-input filter used with a voltage regulator.
- A voltage regulator is connected to the output of a filtered rectifier and maintains a constant output voltage (or current) despite changes in the input, the load current, or the temperature.
- The capacitor- input filter reduces the input ripple to the regulator to an acceptable level.
- The combination of a large capacitor and a voltage regulator helps produce an excellent power supply.
- Most regulators are integrated circuits and have three terminals—an input terminal, an output terminal, and a reference (or adjust) terminal.
- The input to the regulator is first filtered with a capacitor to reduce the ripple to <10%

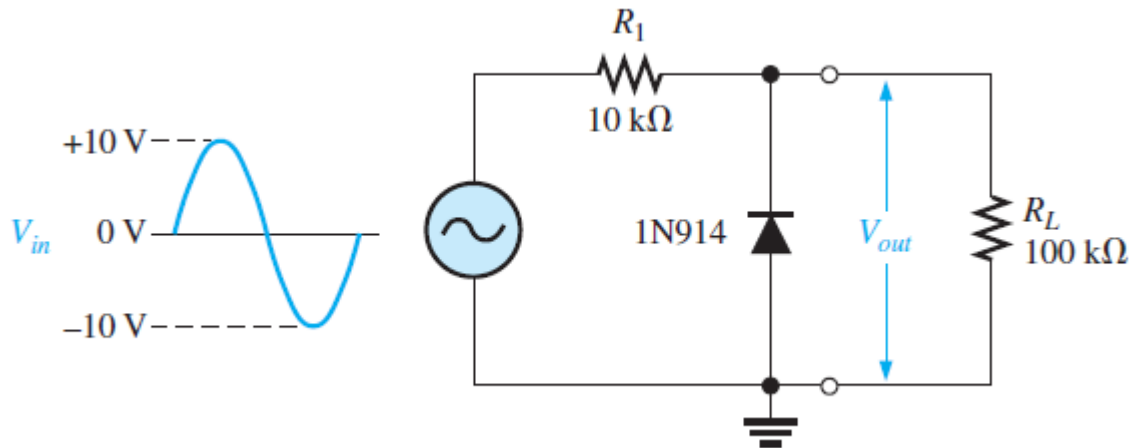
Example

- A certain 7805 regulator has a measured no-load output voltage of 5.18 V and a full load output of 5.15 V. What is the load regulation expressed as a percentage?
- ***Solution***

$$\text{Load regulation} = \left(\frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}} \right) 100\% = \left(\frac{5.18 \text{ V} - 5.15 \text{ V}}{5.15 \text{ V}} \right) 100\% = \mathbf{0.58\%}$$

Example

- What would you expect to see displayed on an oscilloscope connected across R_L in the limiter shown in Figure below.

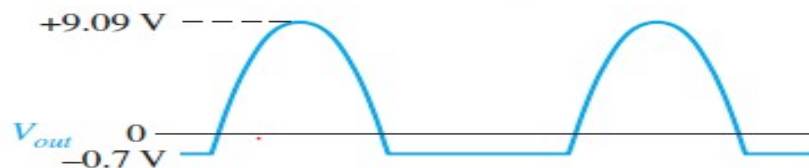


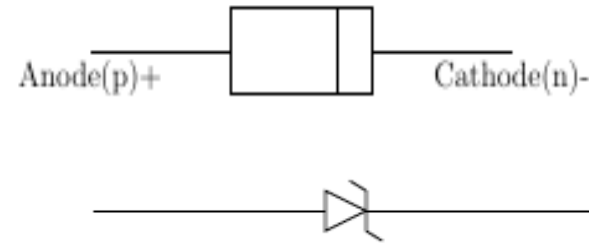
- Solution**

The diode is forward-biased and conducts when the input voltage goes below -0.7 V . So, for the negative limiter, determine the peak output voltage across R_L by the following equation:

$$V_{p(out)} = \left(\frac{R_L}{R_1 + R_L} \right) V_{p(in)} = \left(\frac{100\text{ k}\Omega}{110\text{ k}\Omega} \right) 10\text{ V} = 9.09\text{ V}$$

The scope will display an output waveform as shown in Figure 2–54.



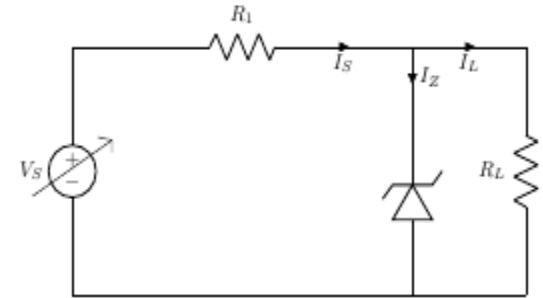


Zener Diode

- A Zener Diode is a special kind of diode which permits current to flow in the forward direction as normal, but will also allow it to flow in the reverse direction when the voltage is above the breakdown voltage or 'zener' voltage.

Zener diodes are designed so that their breakdown voltage is much lower - for example just 2.4 Volts.

Function of Zener Diode



- Zener diodes are a special kind of diode which permits current to flow in the forward direction.
- Zener diodes will also allow current to flow in the reverse direction when the voltage is above a certain value. This breakdown voltage is known as the Zener voltage.
- In a standard diode, the Zener voltage is high, and the diode is permanently damaged if a reverse current above that value is allowed to pass through it.
- In the reverse bias direction, there is practically no reverse current flow until the breakdown voltage is reached. When this occurs there is a sharp increase in reverse current. Varying amount of reverse current can pass through the diode without damaging it. The breakdown voltage or zener voltage (V_Z) across the diode remains relatively constant.

Transistors

- A transistor is a semiconductor device that **amplifies**, oscillates, or **switches** the flow of current between two terminals by varying the current or voltage between one of the terminals and a third.
- transistor is a semiconductor device which transfers the weak signal from low resistance circuit to high resistance circuit.
- A diode is also a semiconductor device in which current flows only in one direction.

- Purpose

- To amplify and switch electronic signals on or off (high or low)

- Modern Electronics



Microprocessor



Cell Phones

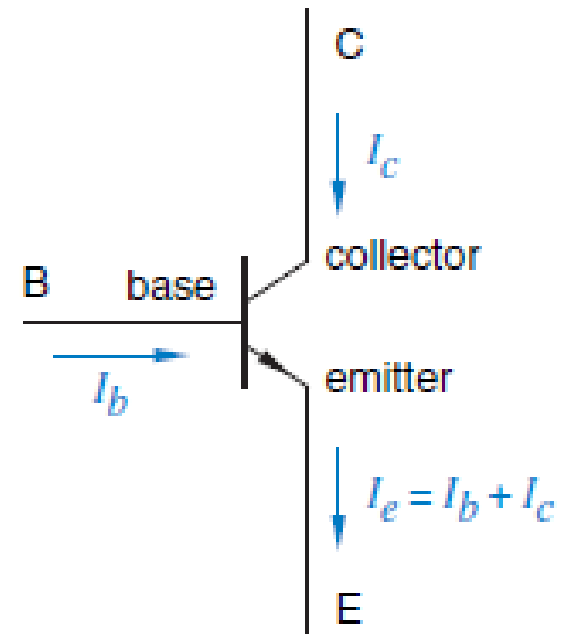


Motor Controllers

- Transistor is an essential component is almost every electronic circuit like: Amplifiers, Switching, Oscillators, Voltage Regulators, Power Supplies and most importantly, the Digital Logic ICs.

BJT Introduction

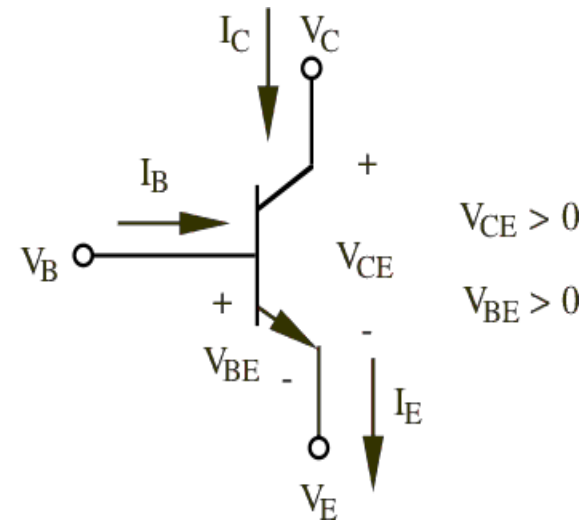
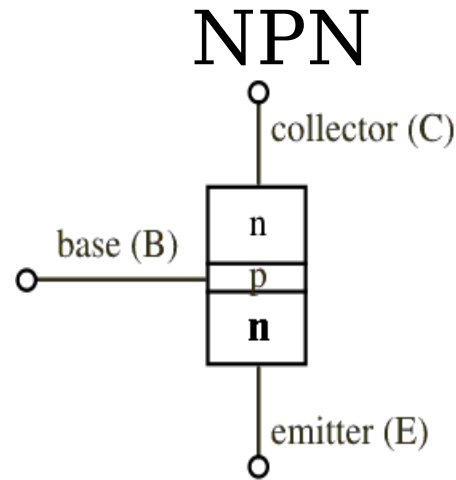
- Bipolar Junction Transistors (BJT) consists of three “sandwiched” semiconductor layers
- The three layers are connected to collector (C), emitter (E), and base (B) pins
- Current supplied to the base controls the amount of current that flows through the collector and emitter



BJT Schematic

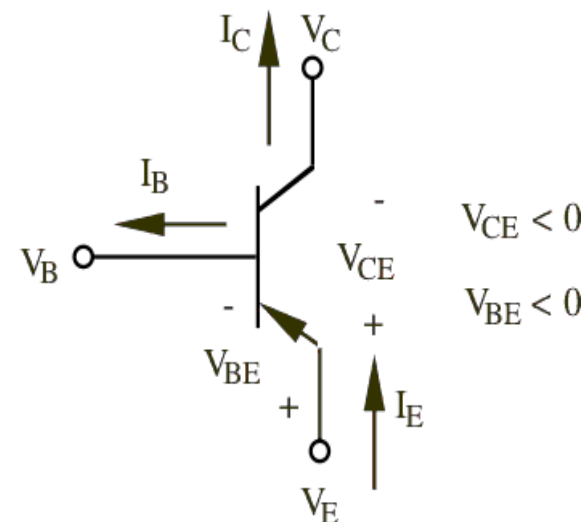
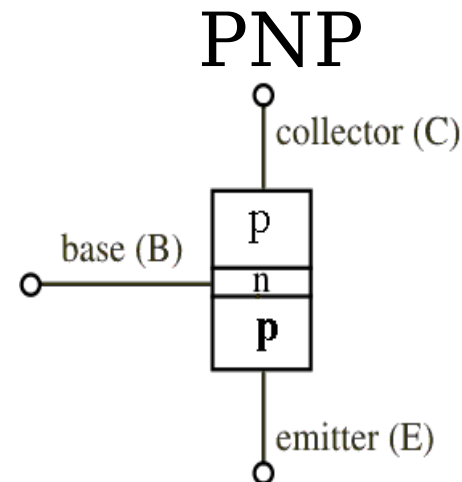
- NPN

- BE forward bias
- BC reverse bias

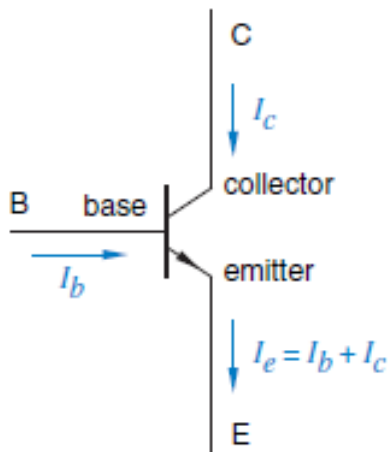
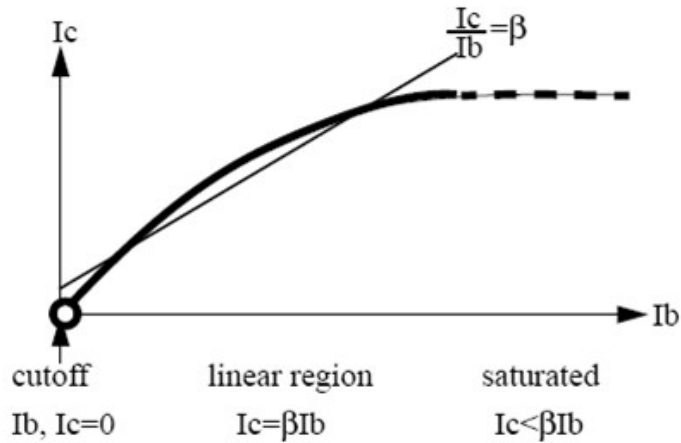


- PNP

- BE reverse bias
- BC forward bias



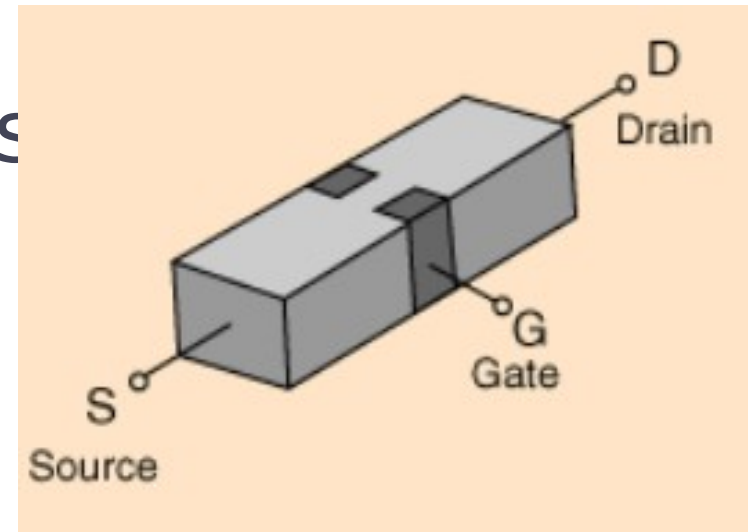
BJT Operating Regions



Operating Region	Parameters	Mode
Cut Off	$V_{BE} < V_{\text{cut-in}}$ $V_{CE} > V_{\text{supply}}$ $I_B = I_C = 0$	Switch OFF
Linear	$V_{BE} = V_{\text{cut-in}}$ $V_{\text{sat}} < V_{CE} < V_{\text{supply}}$ $I_C = \beta * I_B$	Amplification
Saturated	$V_{BE} = V_{\text{cut-in}}$ $V_{CE} < V_{\text{sat}}$ $I_B > I_{C,\text{max}}, I_{C,\text{max}} > 0$	Switch ON

Field Effect Transistors(FET) Basics

- Electric Field
- Voltage Controlled
- FET includes three distinct pieces
 - Drain
 - Source
 - Gate



FET versus BJT?

Same:

- Applications: amplifier, switch, etc.
- Relies on PNP or NPN junctions to allow current flow

Difference:

- Voltage vs Current Input
- Unipolar vs Bipolar
- Noise
- Higher input impedance
- Fragile and low gain

bandwidth

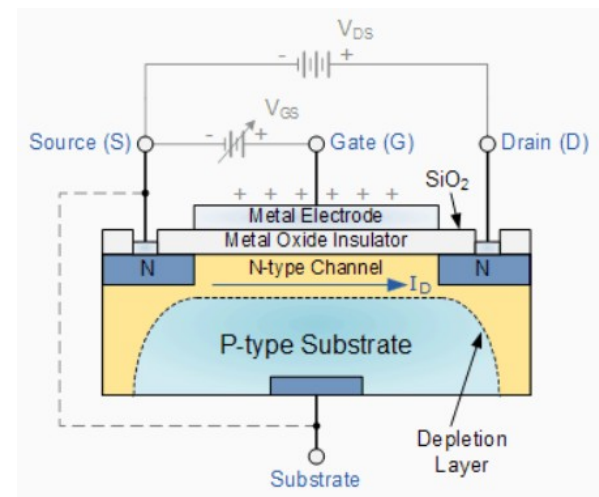
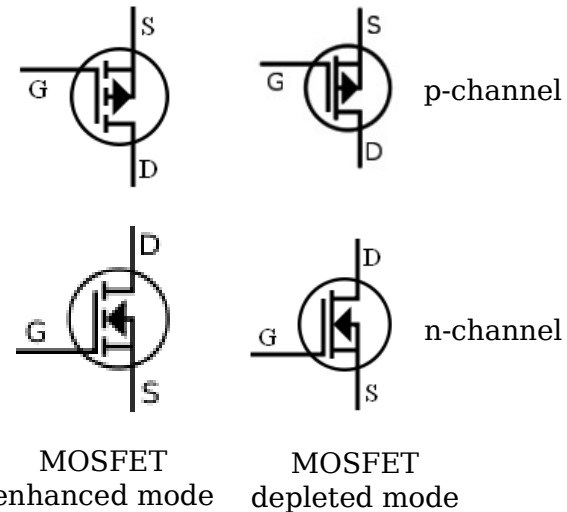
FET	BJT	
Input voltage controls output current	Input current controls output current	
Gate	Base	Controls flow of current
Drain	Collector	Current goes out here
Source	Emitter	Current comes in here

Metal oxide semiconductor field-effect transistor

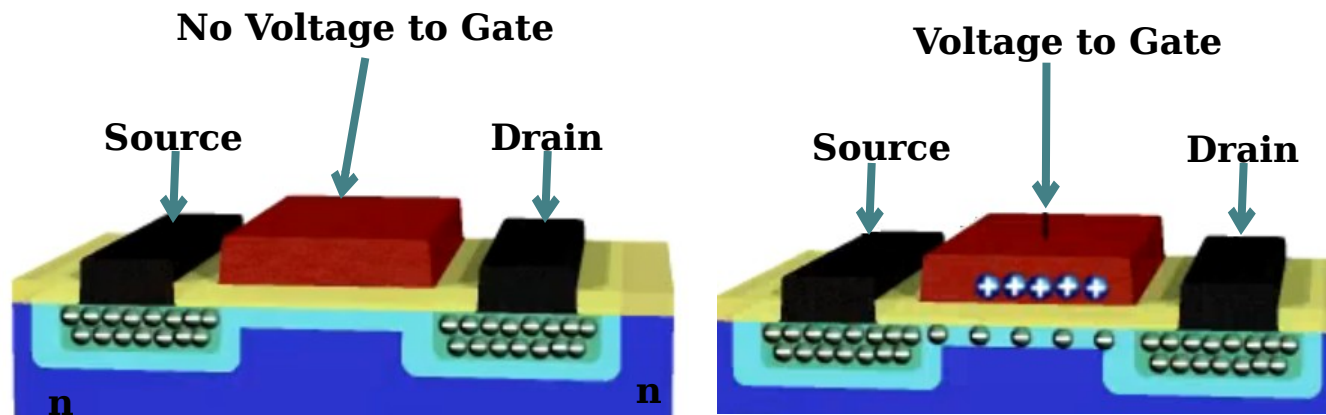
MOSFET

- Similar to JFET

- A single channel of single doped SC material with terminals at end
- Gate surrounds channel with doping that is opposite of the channel, making the PNP or NPN type
- BUT, the MOSFET uses an insulator to separate gate from body, while JFET uses a reverse-bias p-n junction



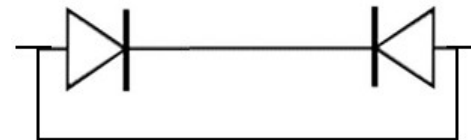
How does a MOSFET work?



Simplified Notation



No current flow



"Short" allows current flow

Power Transistors

- ❖ Concerned with delivering high power
- ❖ Used in high voltage and high current application

In general

Fabrication process different in order to:

- ❖ Dissipate more heat
- ❖ Avoid breakdown

Different types: Power BJTs, power MOSFETs, etc.

Comparison

Property	BJT	MOSFET	JFET
Gm	Best	Worst	Medium
Speed	High	Medium	Low
Noise	Moderate	Worst	Best
Good Switch	No	Yes	Yes
High-Z Gate	No	Yes	Yes
ESD	Less	More	Less

BJT vs MOSFET Transistor

Now that we've covered both types of transistors; BJT and FET (Commonly known MOSFET), let's take a look at their differences shown in the table below:

Which transistor should you choose?

Although MOSFET holds advantages over BJT such as voltage control, choosing either comes down to your application purposes. Here's what each transistor are suitable for:

- If you're looking to regulate the flow of high current in narrow pulses, or for any high power applications, MOSFET is the way to go

- For common electrical circuit usages or low current in-home applications, BJTs may well be sufficient in handling the job

Definition	Metal oxide semiconductor field-effect transistor	Bipolar Junction Transistor
Hardware Construction	3 terminals: Gate, source, drain with higher structure complexity	3 terminals: Emitter, base, and collector
Working Principle	For MOSFET to work, it's dependent on the voltage at the oxide insulated gate electrode	For BJTs to work, it's dependent on the current at the base terminal
Suitability of usage	High power, current control applications Analog and digital circuits	Low-current applications

End of chapter Six