Electronics Devices and Circuits

Semiconductor Physics and Devices

Topics

- Basics of semiconductor physics: Conductors, insulators, semiconductor.
- Diodes: PN-junction, Zener, LEDs
- Transistor fundamentals: BJT, FET
- Device-level applications of diodes and transistors

Intended Learning Outcomes

- Explain the principles of semiconductor physics, including the characteristics of conductors, insulators, and semiconductors.
- Describe the operation of diodes, including PN-junctions, Zener diodes, and LEDs.
- Understand the fundamentals of transistors, including BJTs and FETs.
- Analyze device-level applications of diodes and transistors in circuits.

Definition of Terms:

Valence - is the ability of an atom to combine with other atoms. The valence of an atom is determined by the number of electrons in the atom's outermost shell. This shell is referred to as the valence shell. The electrons in the outermost shell are called valence electrons.

Covalent Bonding - is the sharing of valence electrons between two or more atoms. It is the bonding that holds the atoms together in an orderly structure called a crystal.

Ionization - is the process by which an atom losses or gains electrons. An atom that loses some of its electrons in the process becomes positively charged and is called a positive ion. An atom that has an excess number of electrons is negatively charged and is called a negative ion.

Definition of Terms:

Doping - is the process by which small amounts of selected additives, called impurities are added to semiconductors to increase their current flow. Semiconductors that undergo this treatment are referred to as extrinsic semiconductors.

Forward Bias - is an external voltage that is applied to a PN Junction to reduce its barrier and, therefore, aid current flow through the junction.

Electron's Energy Level - is the amount of energy required by an electron to stay in orbit.

Definition of Terms:

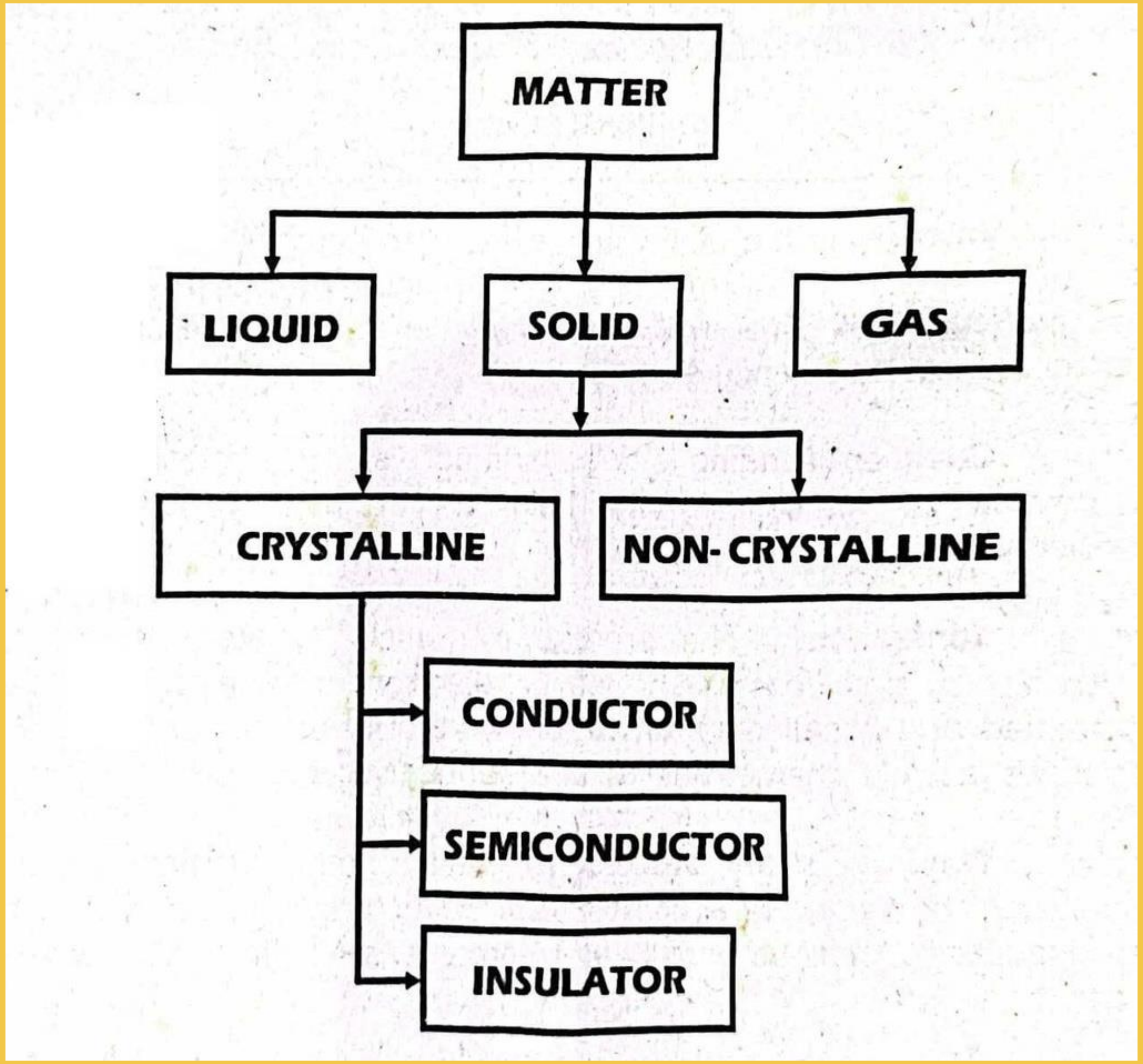
Junction Barrier - is an electrostatic field that has been created by the joining of a section of N material with a section of P material

Voltage-controlled device - are devices that utilizes static voltage as the controlling signal.

Current-controlled device - are devices working on the principle of one current controlling another current.

Transistor - is a three or more element solid-state device that amplifies by controlling the current carriers through its semiconductors.

Solid State Physics



Solid State Physics

Solid

Solids are materials in which the atoms or molecules are set in place.

Crystalline solids have characteristics angles and can be cleaved along lines defined by the aligning of atoms or molecules of the crystal.

Amorphous (without crystal shape) solids can be like carbon black or linked as in plastics. The common point about solids is that the atoms or molecules are in place.

Solid State Physics

Solid is further divided into two parts:

- Crystalline
- Non - crystalline

Crystalline solids can be further divided into three categories:

- Conductor
- Insulator
- Semiconductor

Solid State Physics

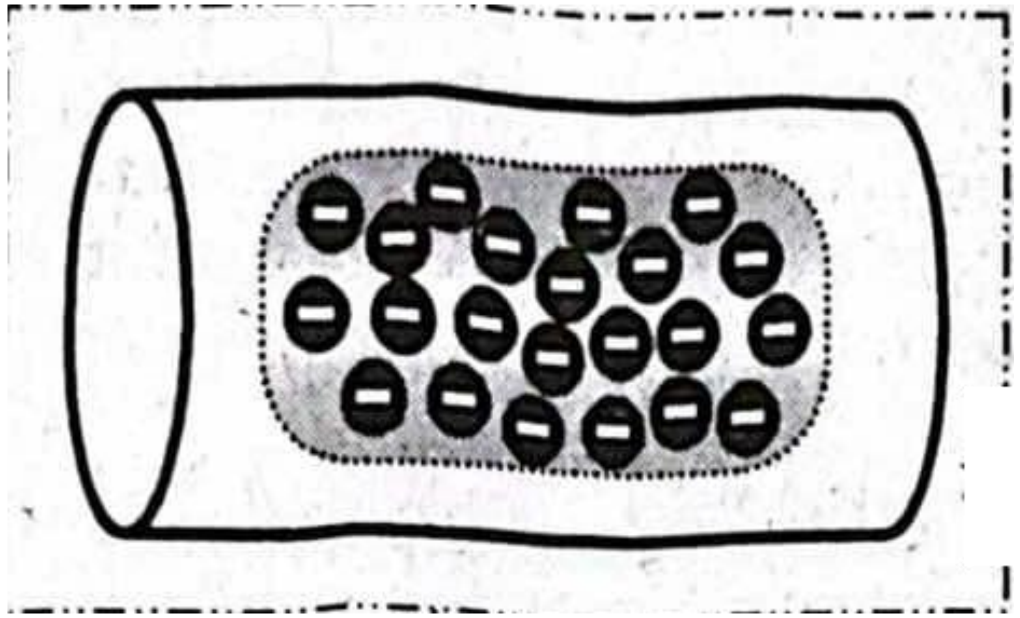
Lattice Crystal system

- **Lattice**
  An infinite array of points in space, in which each point has identical surroundings to all others.
- **Crystal structure**
  The periodic arrangement of atoms in the crystal.
- **Unit cell**
  The smallest component of the crystal, which when stacked together with pure translational repetition reproduces the whole crystal.

3 BROAD CATEGORIES OF MATERIALS

Conductors

Conductors are elements which conduct electricity very readily.

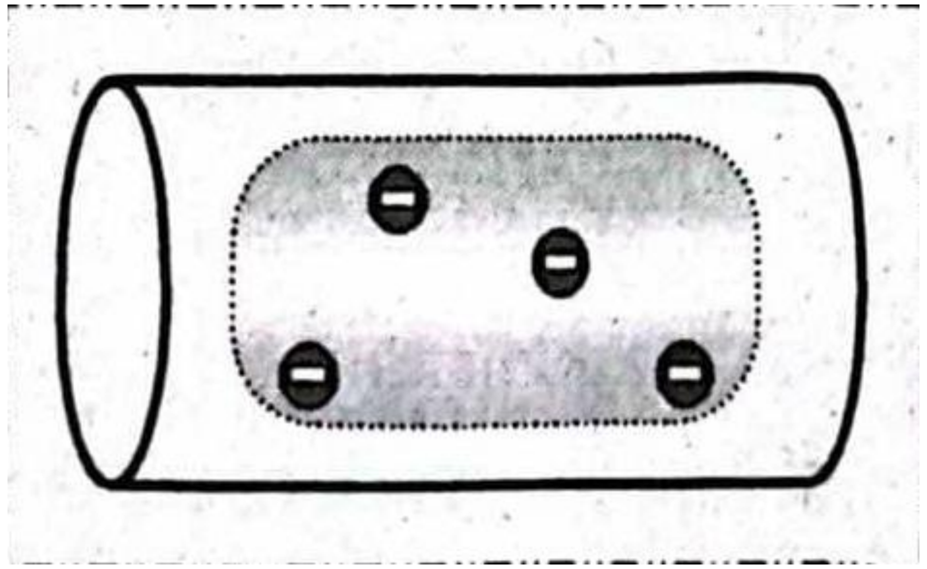


- Conductors have three or less valence electrons.
- Conductors exhibit positive temperature coefficient.
- Examples: Silver, copper, gold and aluminum.
- Silver is the best conductor, followed by copper, gold and aluminum.

3 BROAD CATEGORIES OF MATERIALS

Insulators

Insulators have extremely high resistance to the flow of electricity.

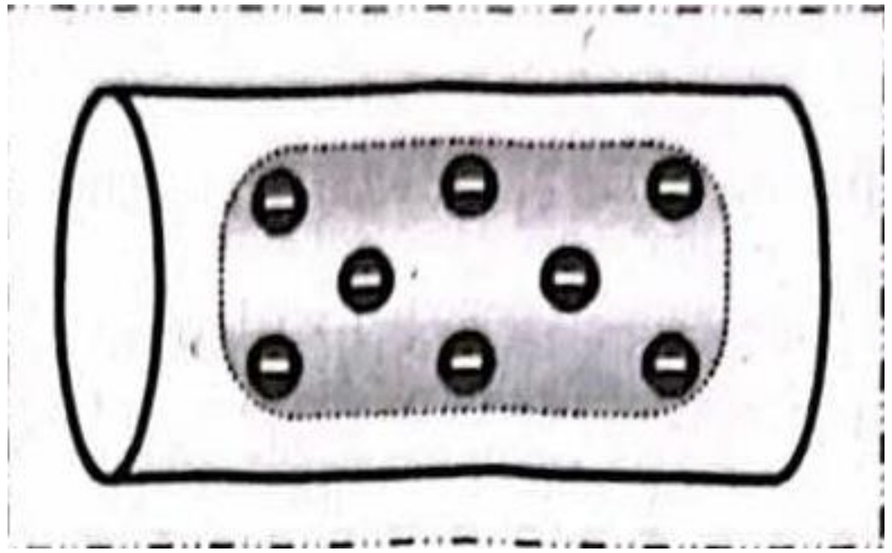


- Insulators have five or more valence electrons.
- Insulators exhibit negative temperature coefficient.
- Examples: Rubber, plastic, enamel, glass, dry wood and mica.

3 BROAD CATEGORIES OF MATERIALS

Semiconductors

All matter between these two extremes (conductors and insulators) may be called semiconductors.

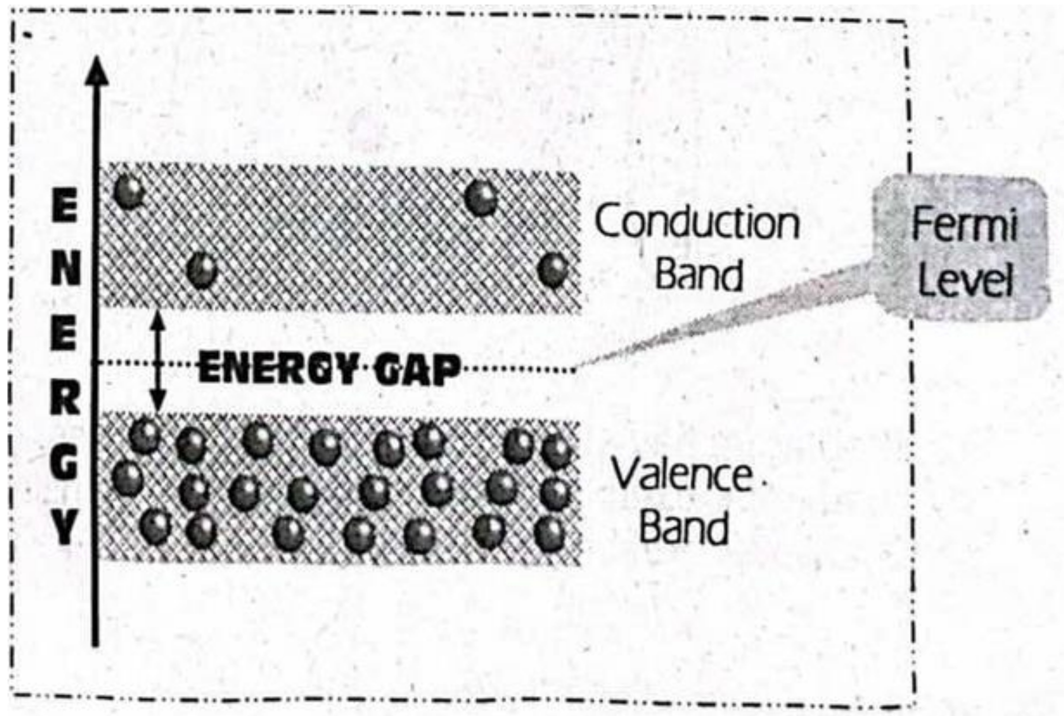


- Semiconductors usually have four valence electrons.
- Semiconductors exhibit negative temperature coefficient.
- Examples: Germanium, silicon, and carbon.

BAND THEORY OF SOLIDS

Semiconductor Energy Bands

For intrinsic semiconductors like silicon and germanium, the Fermi level is essentially halfway between the valence and conduction bands. Although no conduction occurs at 0 K, at higher temperatures a finite number of electrons can reach the conduction band and provide some current.

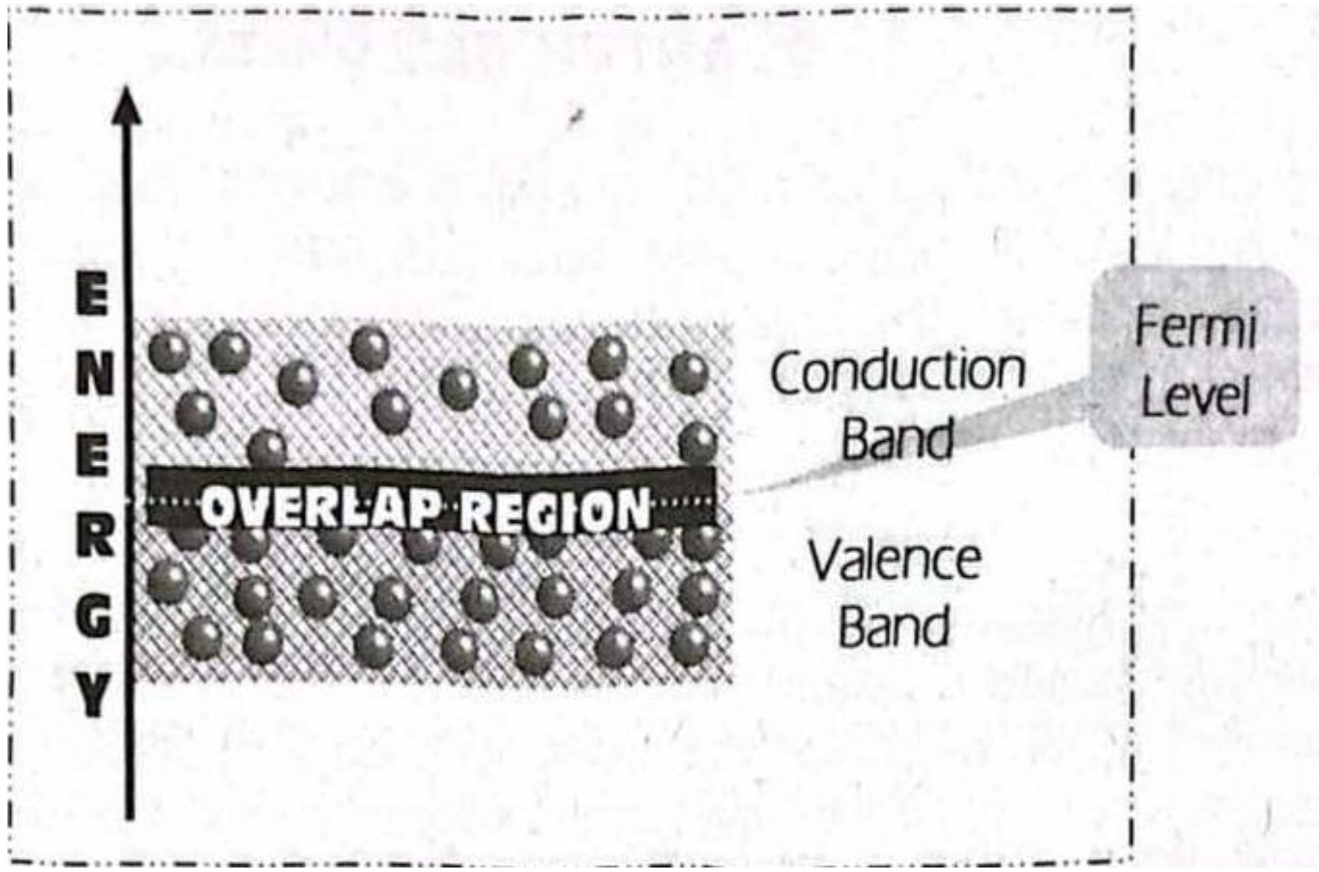


Materials	Energy Gap
Germanium	E_g=0.67 eV
Silicon	E_g=1.11 eV
Gallium Phosphide	E_g=1.41 eV

BAND THEORY OF SOLIDS

Conductor Energy Bands

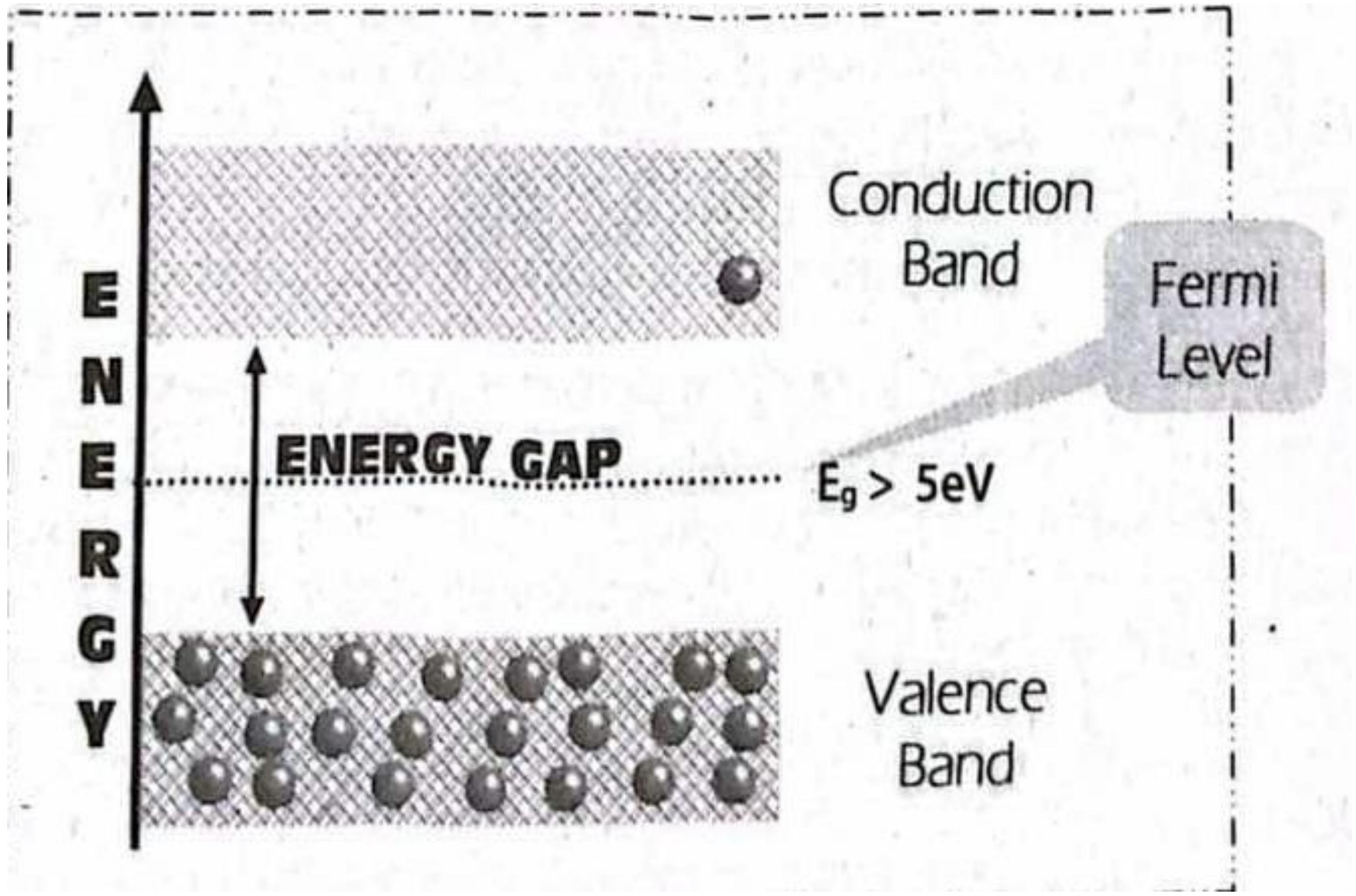
In terms of the band theory of solids, metals are unique as good conductors of electricity. This can be seen to be a result of their valence electrons being essentially free. In the band theory, this is depicted as an overlap of the valence band and the conduction band so that at least a fraction of the valence electrons can move through the material.



BAND THEORY OF SOLIDS

Insulator Energy Bands

Most solid substances are insulators, and in terms of the band theory of solids this implies that there is a large forbidden gap between the energies of the valence electrons and the energy at which the electrons can move freely through the material.



SEMICONDUCTOR FUNDAMENTALS

Intrinsic and Extrinsic Semiconductors

- **Intrinsic Semiconductors**

  Semiconductors that have been carefully refined to reduce the impurities to a very low level.

- **Extrinsic Semiconductors**

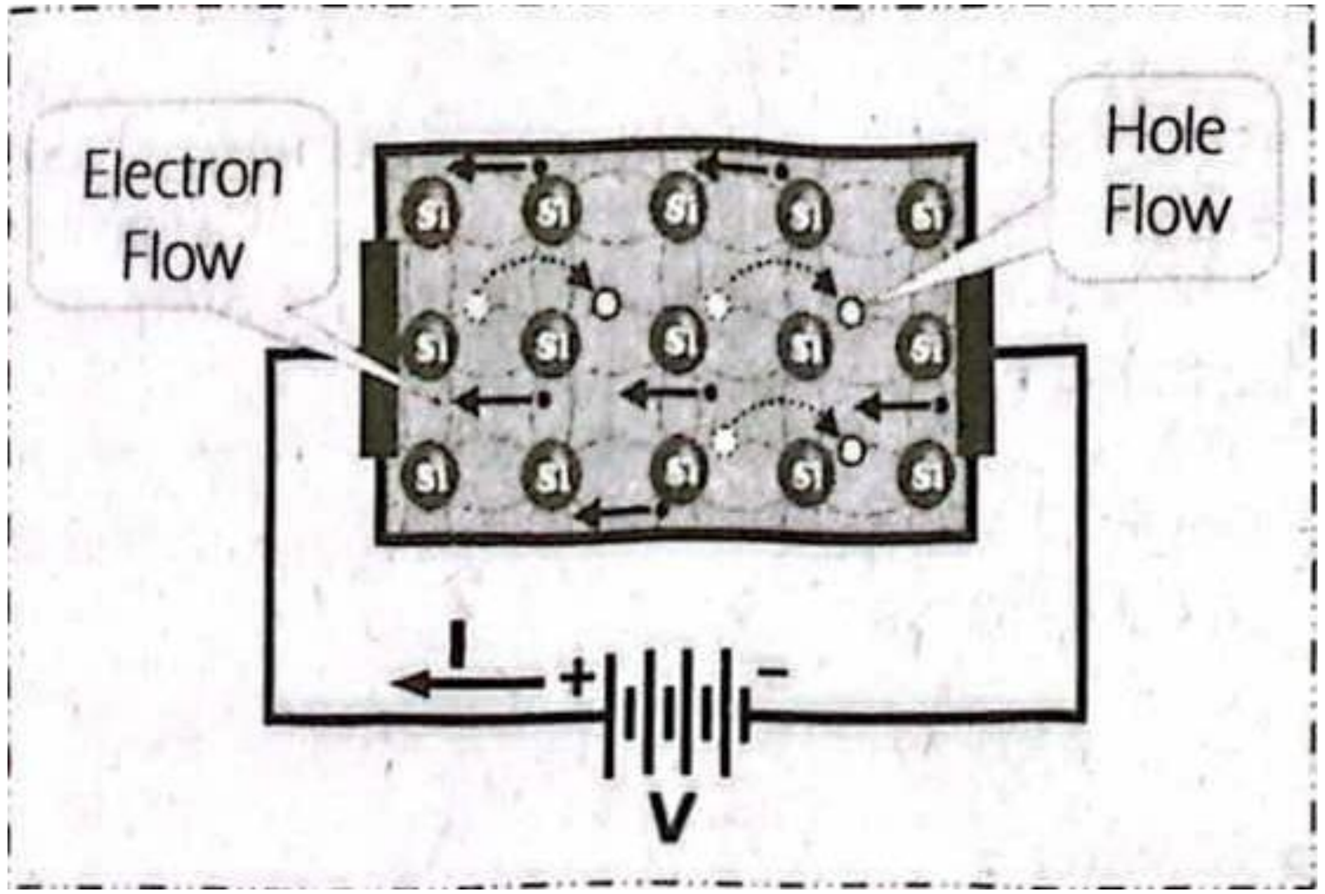
  A semiconductor material that has been subjected to the doping process is called extrinsic semiconductors.

  Hole - the absence of an electron in the valence band of an atom.
  Free electrons - an electron that has acquired enough energy to break away from the valence band of the parent atom, also called as conduction electron.

SEMICONDUCTOR FUNDAMENTALS

Current flow in intrinsic semiconductor materials

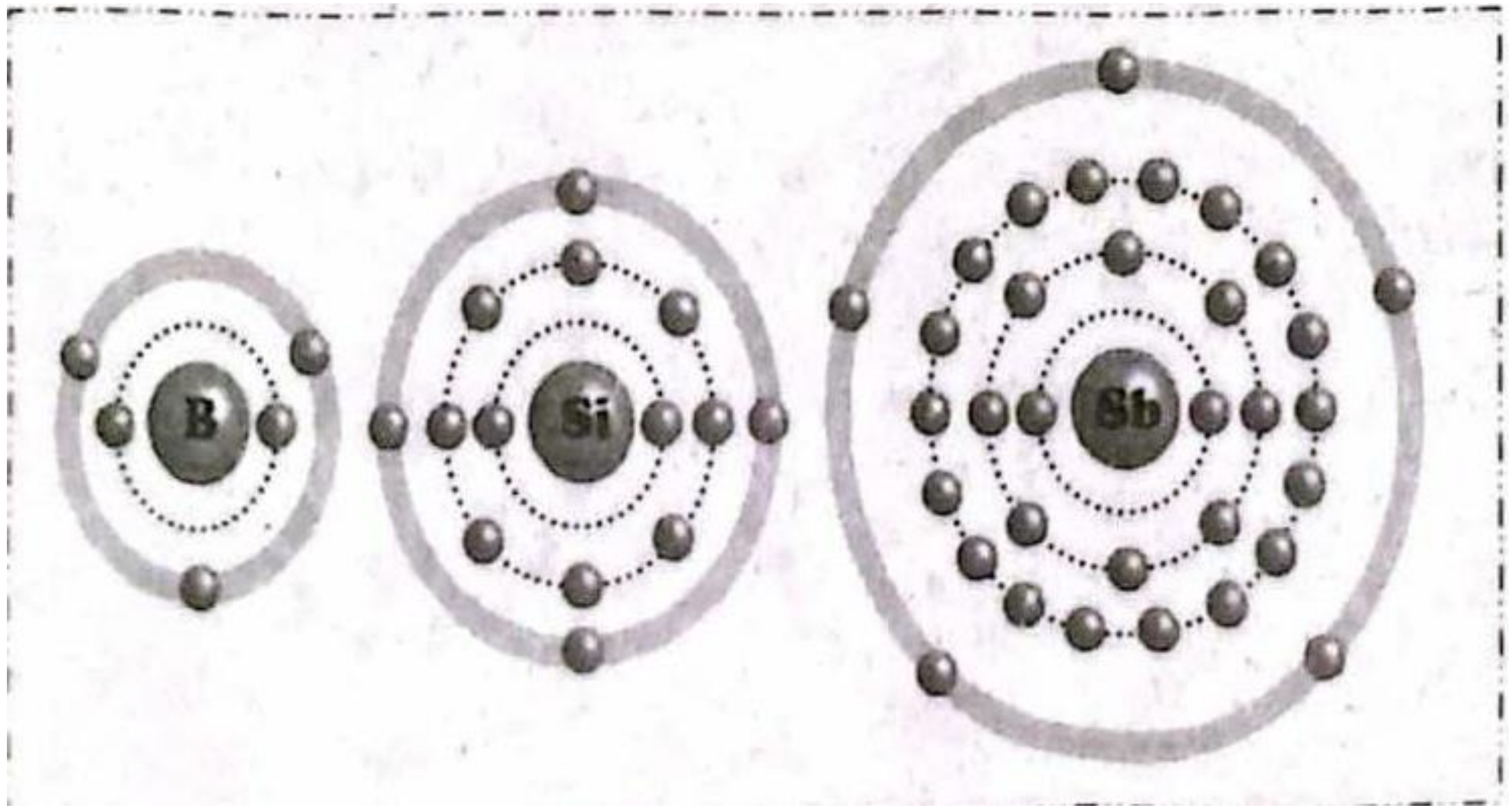
The current which will flow in an intrinsic semiconductor consists of both electron and hole current. That is, the electrons which have been freed from their lattice positions



SEMICONDUCTOR FUNDAMENTALS

Valence Electrons

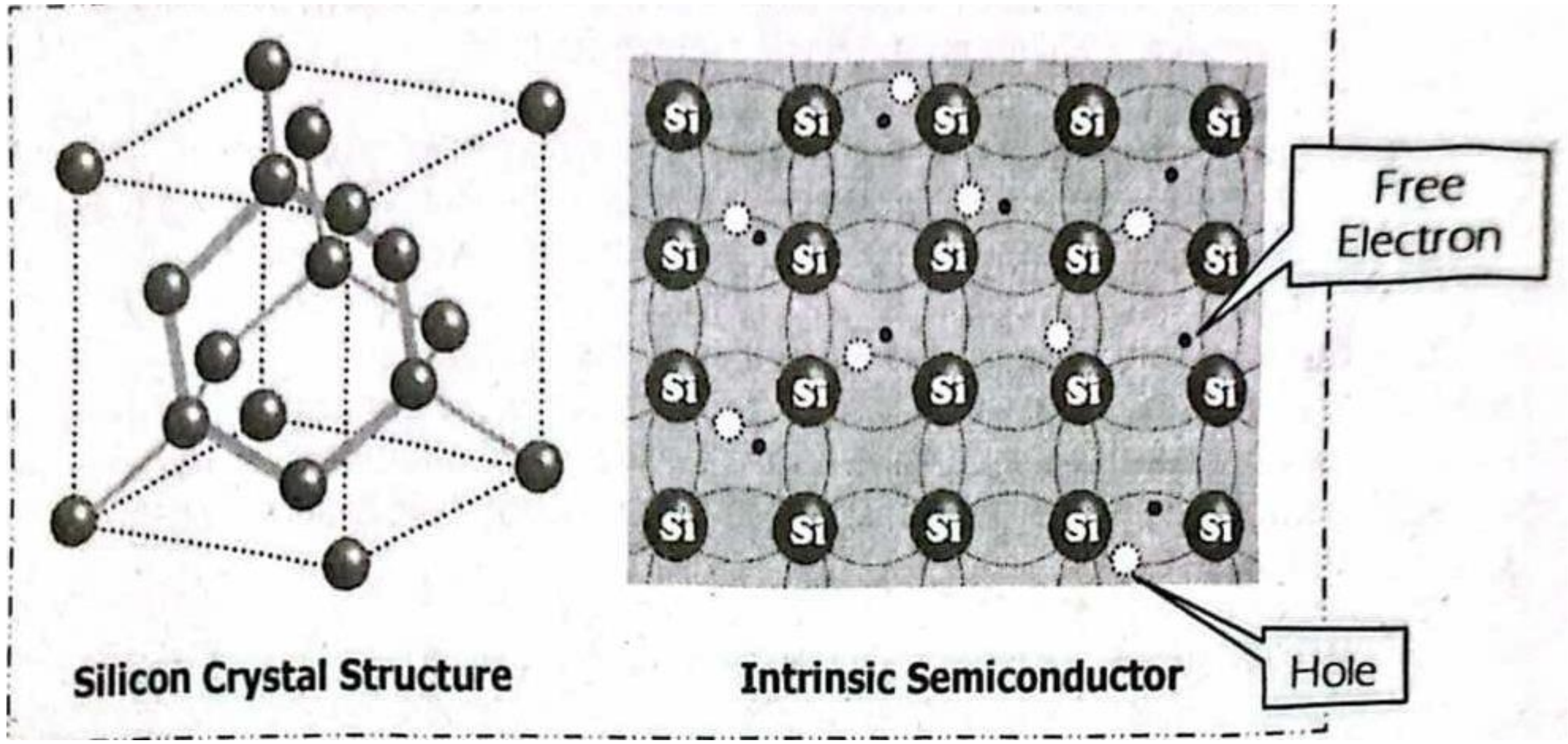
The electrons in the outermost shell of an atom are called valence electrons; they dictate the nature of the chemical reactions of the atom and largely determine the electrical nature of a solid matter.



SEMICONDUCTOR FUNDAMENTALS

Silicon and Germanium Crystals

Solid state electronics arises from the unique properties of silicon and germanium, each of which has four valence electrons and which form crystal lattices in which substituted atoms (dopants) can dramatically change the electrical properties.



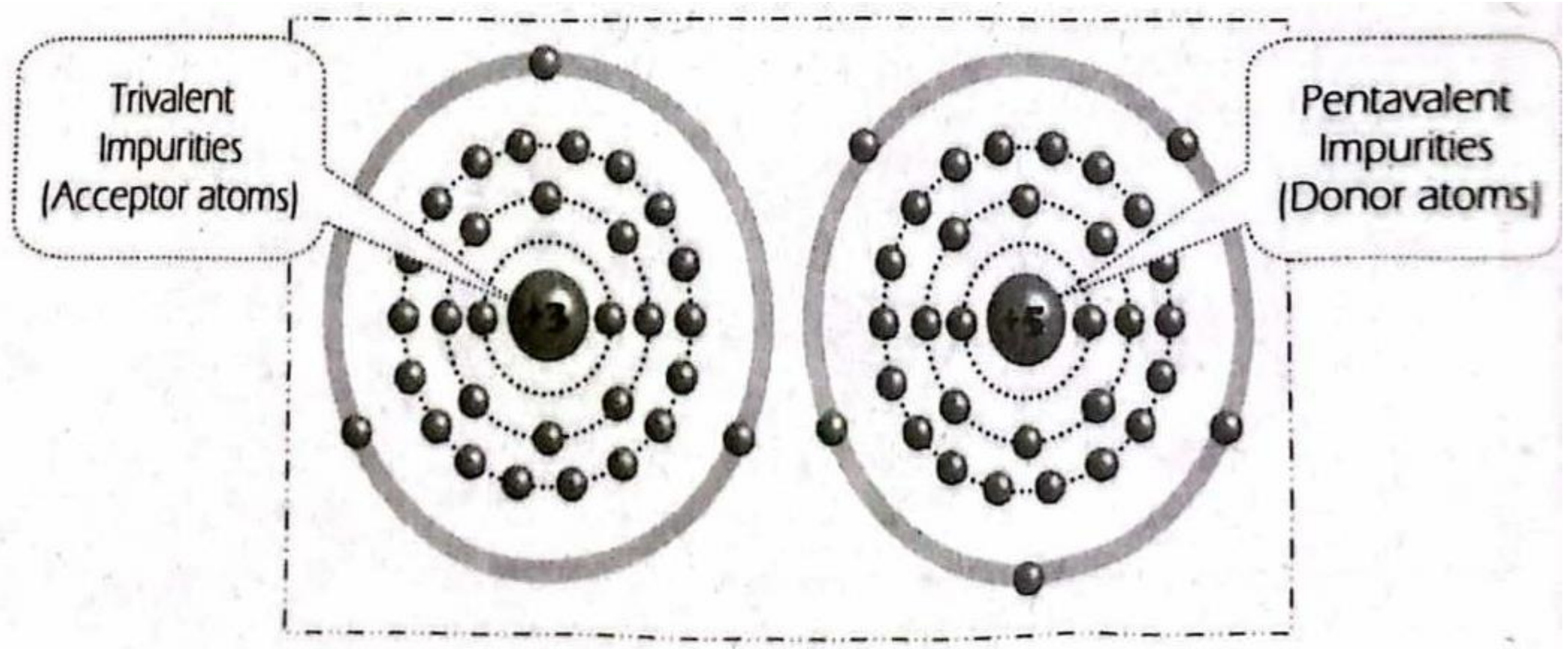
SEMICONDUCTOR FUNDAMENTALS

A silicon crystal is different from an insulator because at any temperature above absolute zero temperature, there is a finite probability that an electron in the lattice will be knocked loose from its position leaving behind an electron deficiency called a “hole”.

The cube side for silicon is 0.543 nm. Germanium has the same diamond structure with a cell dimension of 0.566 nm.

SEMICONDUCTOR FUNDAMENTALS

Semiconductor Doping
The addition of a small percentage of foreign atoms in the regular crystal lattice of silicon or germanium produces dramatic changes in their electrical properties, producing n-type and p-type semiconductors.



SEMICONDUCTOR FUNDAMENTALS

- **Pentavalent Impurities (Donor atoms)**
  Impurity atoms with 5 valence electrons produce N-type semiconductors by contributing extra electrons.

Impurities	Symbol	Atomic Number	Atomic Structure	Distribution	
				P	E
Phosporus	P	15	Monoclinic	15	15
Arsenic	As	33	Rhombohedral	33	33
Antimony	Sb	51	------	51	51

P=proton, E=electron

SEMICONDUCTOR FUNDAMENTALS

- **Trivalent Impurities**
  Impurity atoms with 3 valence electrons produce P-type semiconductors by producing a “hole” or electron deficiency.

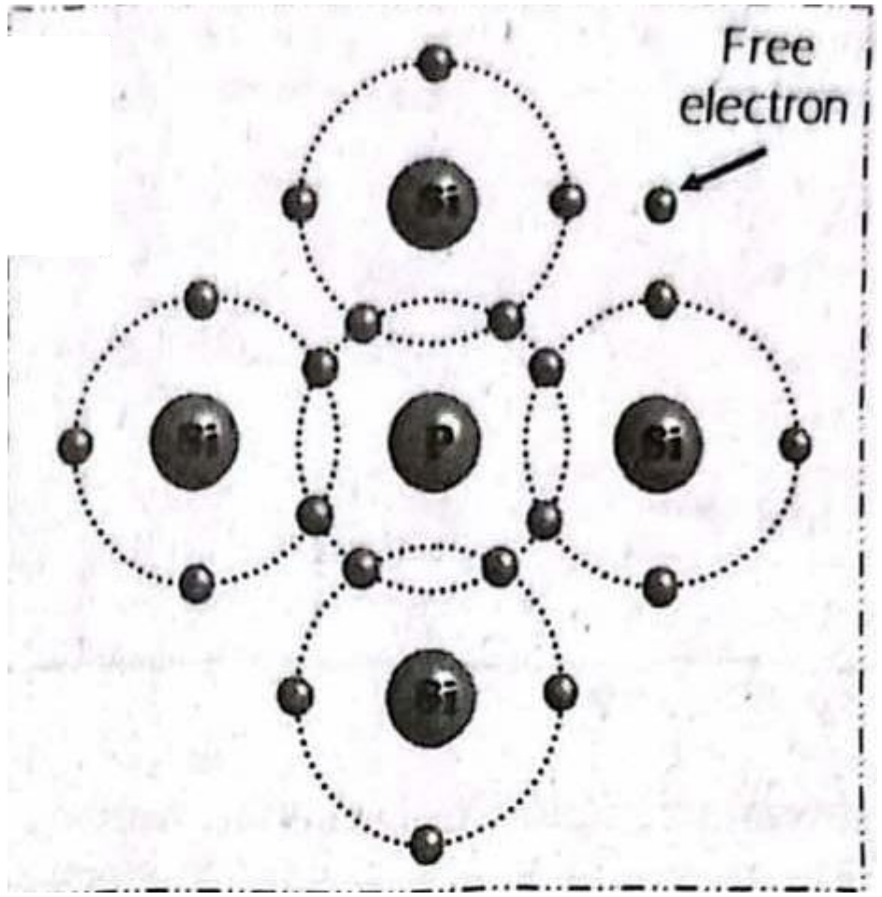
Impurities	Symbol	Atomic Number	Atomic Structure	Distribution	
				P	E
Boron	B	5	Rhombohedral	5	5
Aluminum	Al	13	Face-centered cubic	13	13
Gallium	Ga	31	Orthorhombic	31	31
Indium	In	49	Tetragonal	49	49

P=proton, E=electron

SEMICONDUCTOR FUNDAMENTALS

Two general types of semiconductor

- **N-Type Semiconductor**
  The addition of pentavalent impurities such as antimony, arsenic or phosphorous contributes free electrons greatly increasing the conductivity of the intrinsic semiconductor.

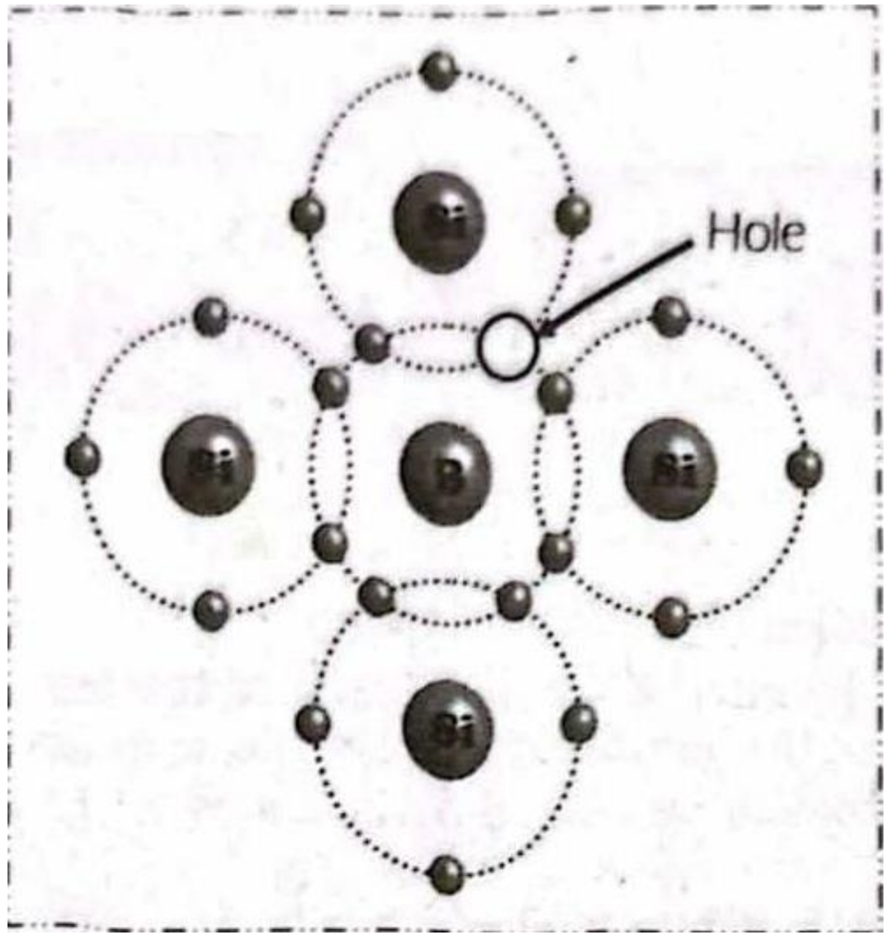


SEMICONDUCTOR FUNDAMENTALS

- **N-Type Band Structure**
  The addition of donor impurities contributes electron energy levels high in the semiconductor band gap so that the electrons can be easily excited into the conduction band.

SEMICONDUCTOR FUNDAMENTALS

- **P-Type Semiconductor**
  The addition of trivalent impurities such as boron, aluminum or gallium to an intrinsic semiconductor creates deficiencies of valence electrons, called “holes”.



SEMICONDUCTOR FUNDAMENTALS

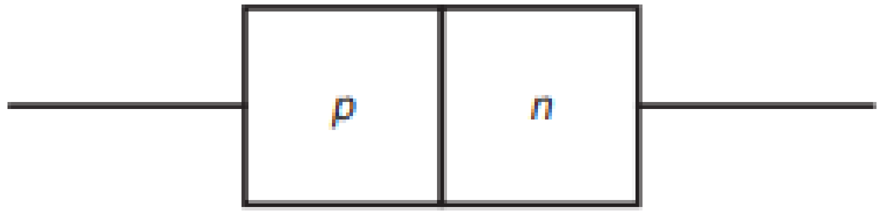
- **P-Type Band Structure**
  The addition of acceptor impurities contributes hole levels low in the semiconductor band gap so that the electrons can be easily excited from the valence band into these levels, leaving mobile holes in the valence band.

Diode Fundamentals

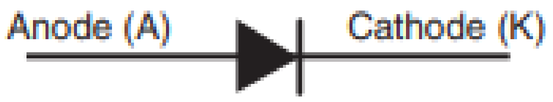
The p-n Junction Diode

A popular semiconductor device called a diode is made by joining p - and n - type semiconductor materials, as shown in Fig. 1a. Notice that the doped regions meet to form a p-n junction. Diodes are unidirectional devices that allow current to flow through them in only one direction.

The schematic symbol for a semiconductor diode is shown in Fig. 1b. The p side of the diode is called the anode (A), whereas the n side of the diode is called the cathode (K).



(a)

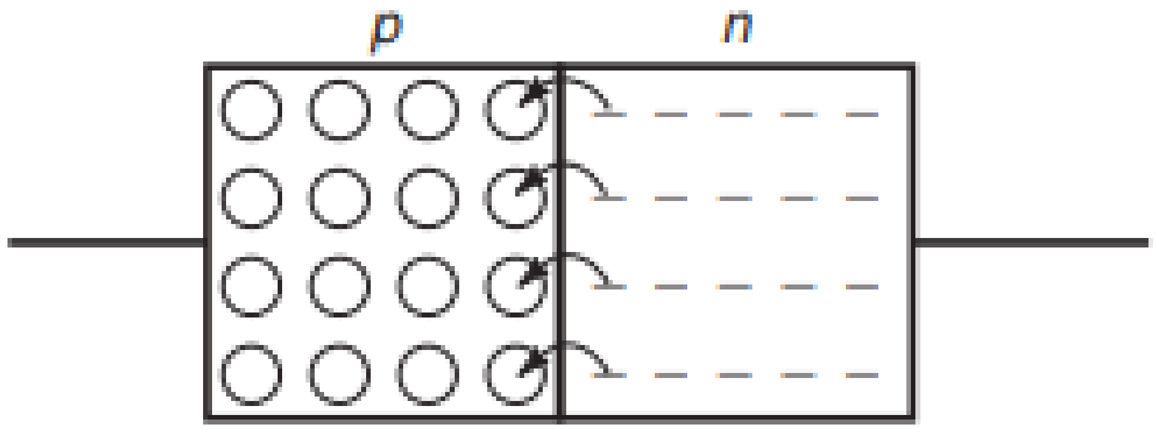


(b)

Diode Fundamentals

Depletion Zone

Figure 2a shows a p - n junction with free electrons on the n side and holes on the p side. Notice that the free electrons are represented as dash (–) marks and the holes are represented as small circles (o).



(a)

Diode Fundamentals

Depletion Zone

At the instant the p - n junction is formed, free electrons on the n side migrate or diffuse across the junction to the p side. Once on the p side, the free electrons are minority current carriers. The lifetime of these free electrons is short, however, because they fall into holes shortly after crossing over to the p side. The important effect here is that when a free electron leaves the n side and falls into a hole on the p side, two ions are created: a positive ion on the n side and a negative ion on the p side (see Fig. 2b).

Diode Fundamentals

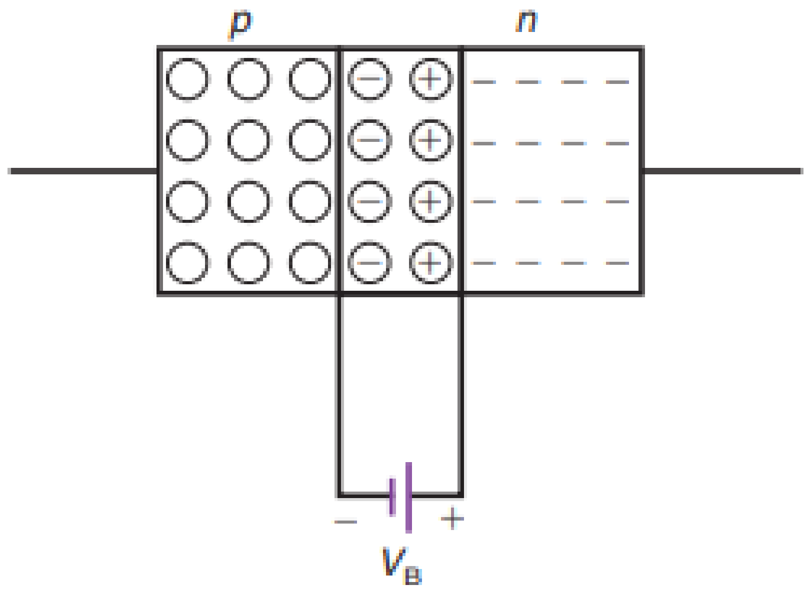
Depletion Zone

As the process of diffusion continues, a barrier potential, VB, is created and the diffusion of electrons from the n side to the p side stops. Electrons diffusing from the n side sense a large negative potential on the p side that repels them back to the n side. Likewise, holes from the p side are repelled back to the p side by the positive potential on the n side. The area where the positive and negative ions are located is called the depletion zone. Other names commonly used are depletion region and depletion layer. The word depletion is used because the area has been depleted of all charge carriers. The positive and negative ions in the depletion zone are fixed in the crystalline structure and are therefore unable to move.

Diode Fundamentals

Barrier Potential, VB

Ions create a potential difference at the p - n junction, as shown in Fig. 2b. This potential difference is called the barrier potential and is usually designated VB. For silicon, the barrier potential at the p - n junction is approximately 0.7 V. For germanium, VB is about 0.3 V. The barrier potential cannot be measured externally with a voltmeter, but it does exist at the p - n junction. The barrier potential stops the diffusion of current carriers.

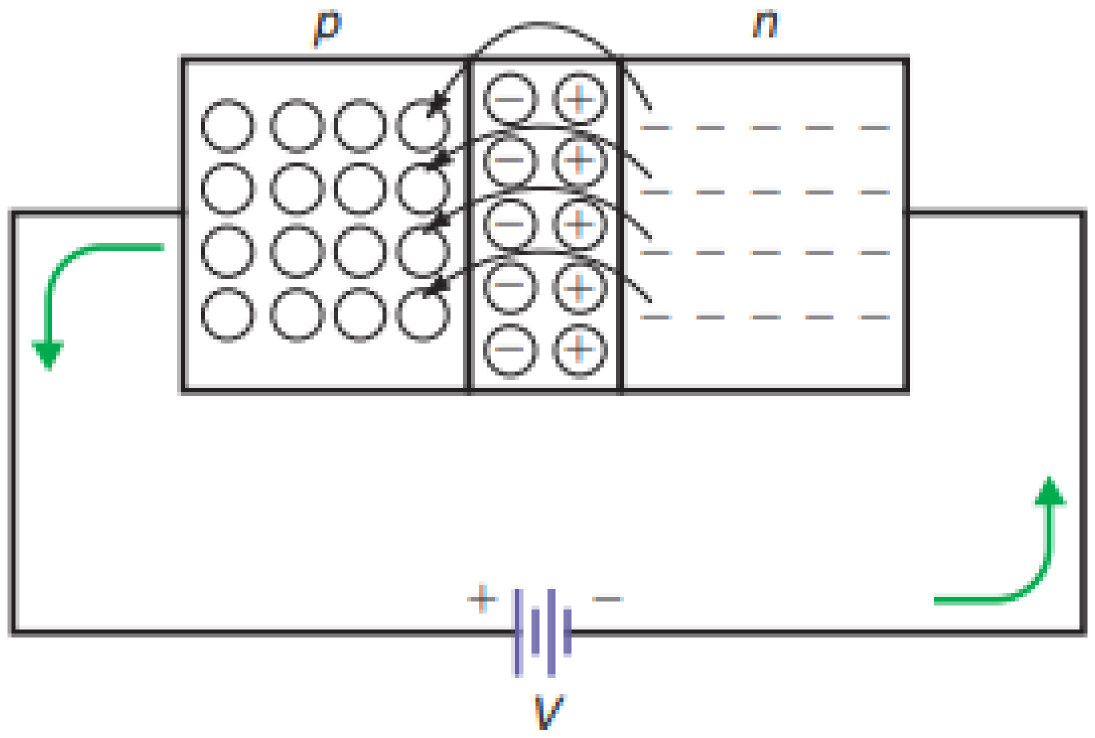


(b)

Diode Fundamentals

Forward Biased P-N Junction

The term bias is defined as a control voltage or current. Forward-biasing a diode allows current to flow easily through the diode. Figure 3a illustrates a p - n junction that is forward-biased.



(a)

Diode Fundamentals

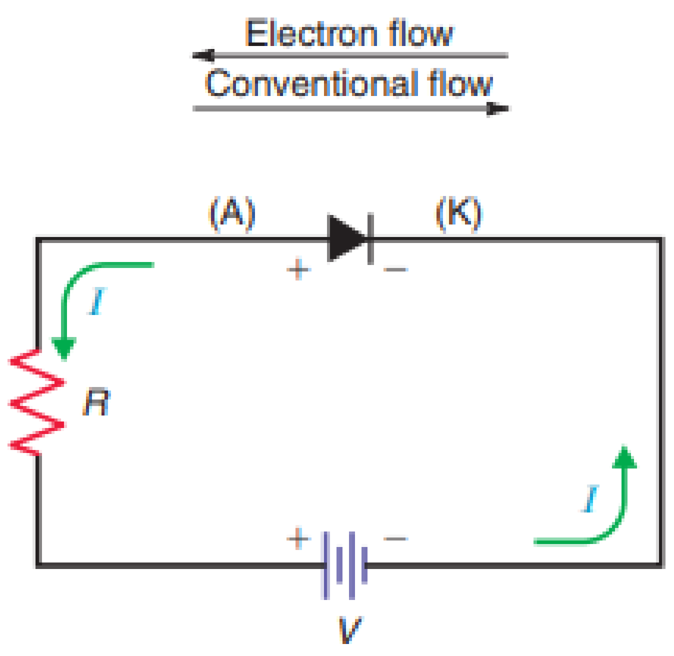
Forward Biased P-N Junction

In Fig. 3a, notice that the n material is connected to the negative terminal of the voltage source, V, and the p material is connected to the positive terminal of the voltage source, V. The voltage source, V, must be large enough to overcome the internal barrier potential VB. The voltage source repels free electrons in the n side across the depletion zone and into the p side. Once on the p side, the free electron falls into a hole. The electron will then travel from hole to hole as it is attracted to the positive terminal of the voltage source, V. For every free electron entering the n side, one electron leaves the p side. Notice in Fig. 3a that if the p - n junction is made from silicon, the external voltage source must be 0.7 V or more to neutralize the effect of the internal barrier potential, VB, and in turn produce current flow. (It should be noted that in a practical circuit, a resistance would be added in series with the diode to limit the current flow.)

Diode Fundamentals

Forward Biased P-N Junction

Figure 3b shows the schematic symbol of a diode with the voltage source, V, connected to provide forward bias. Notice that forward bias exists when the anode, A is positive with respect to the cathode, K. Notice that electrons flow to the n side, against the arrow on the diode symbol. The arrow on the diode symbol points in the direction of conventional current flow.

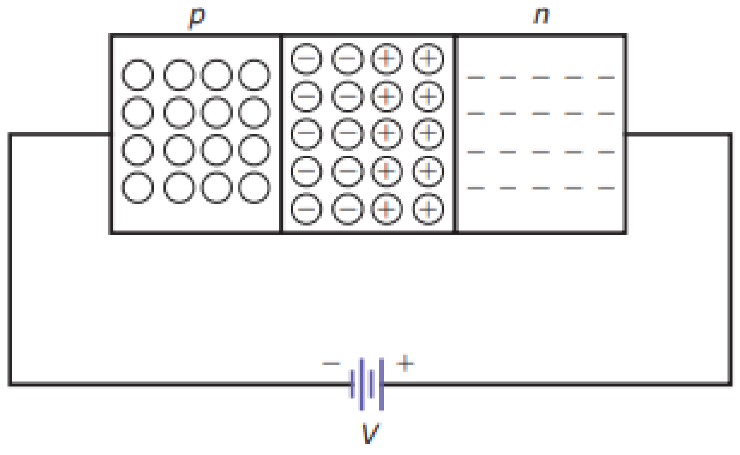


(b)

Diode Fundamentals

Reverse Biased P-N Junction

Figure 4a shows how to reverse-bias a p - n junction. Notice that the negative terminal of the voltage source, V, is connected to the p-type semiconductor material and that the positive terminal of the voltage source, V, is connected to the n-type semiconductor material. The effect is that charge carriers in both sections are pulled away from the junction. This increases the width of the depletion zone, as shown. Free electrons on the n side are attracted away from the junction because of the attraction of the positive terminal of the voltage source, V. Likewise, holes in the p side are attracted away from the junction because of the attraction by the negative terminal of the voltage source, V.

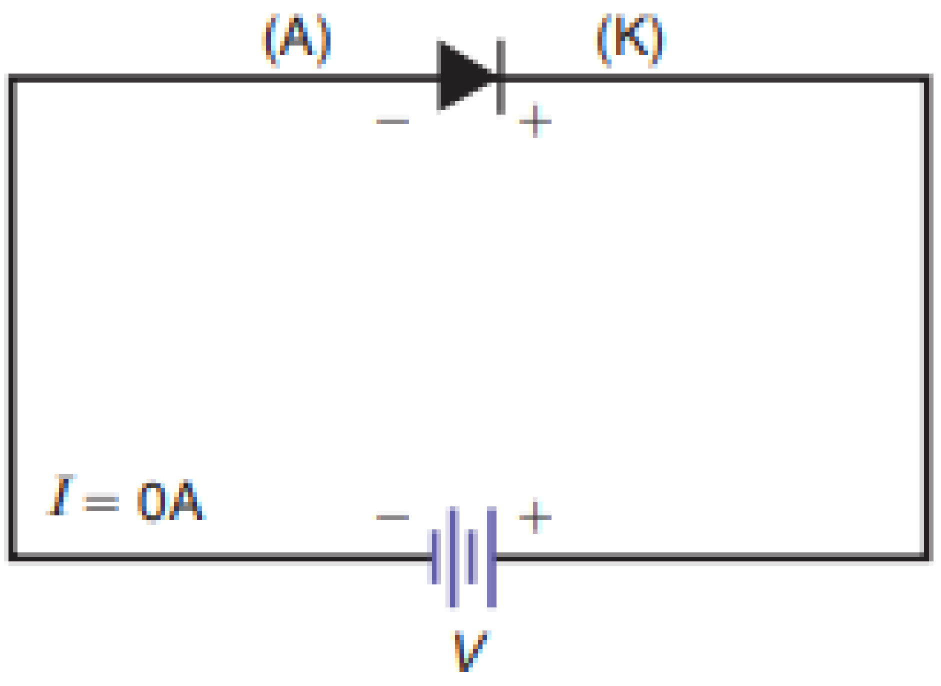


(a)

Diode Fundamentals

Reverse Biased P-N Junction

Figure 4b shows the schematic symbol of a diode with the voltage source, V, connected to provide reverse bias. The result of reverse bias is that the diode is in a nonconducting state and acts like an open switch, ideally with infinite resistance.

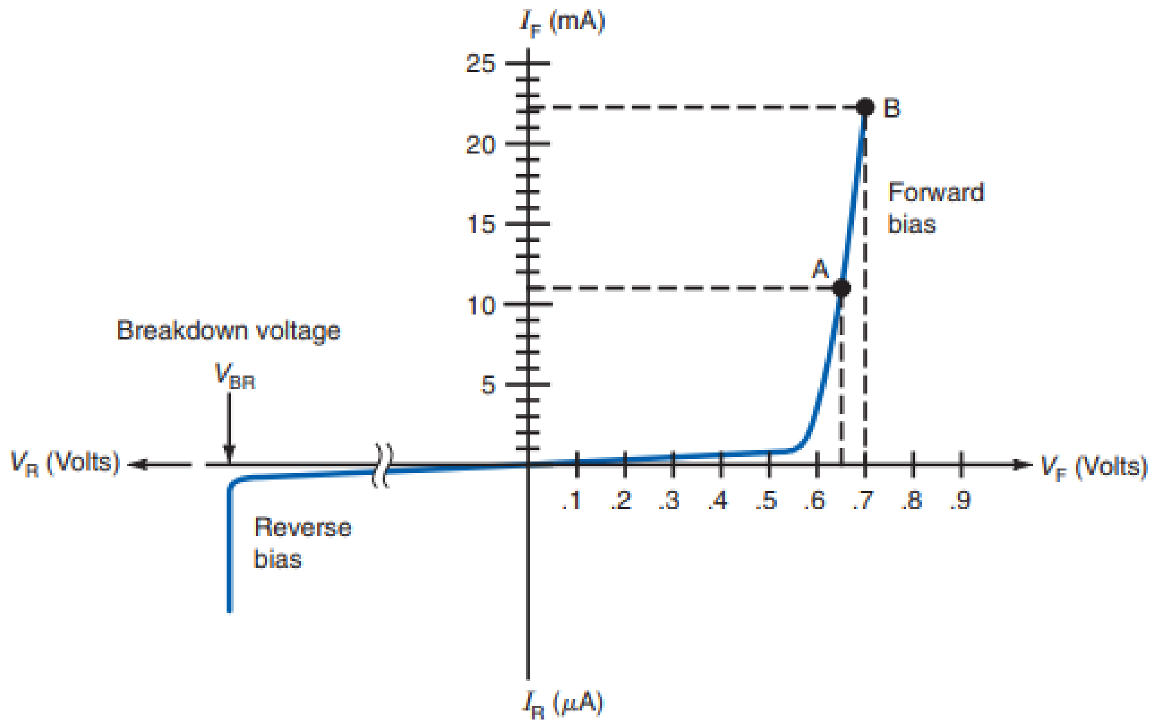


(b)

Diode Fundamentals

Volt-Ampere Characteristic Curve

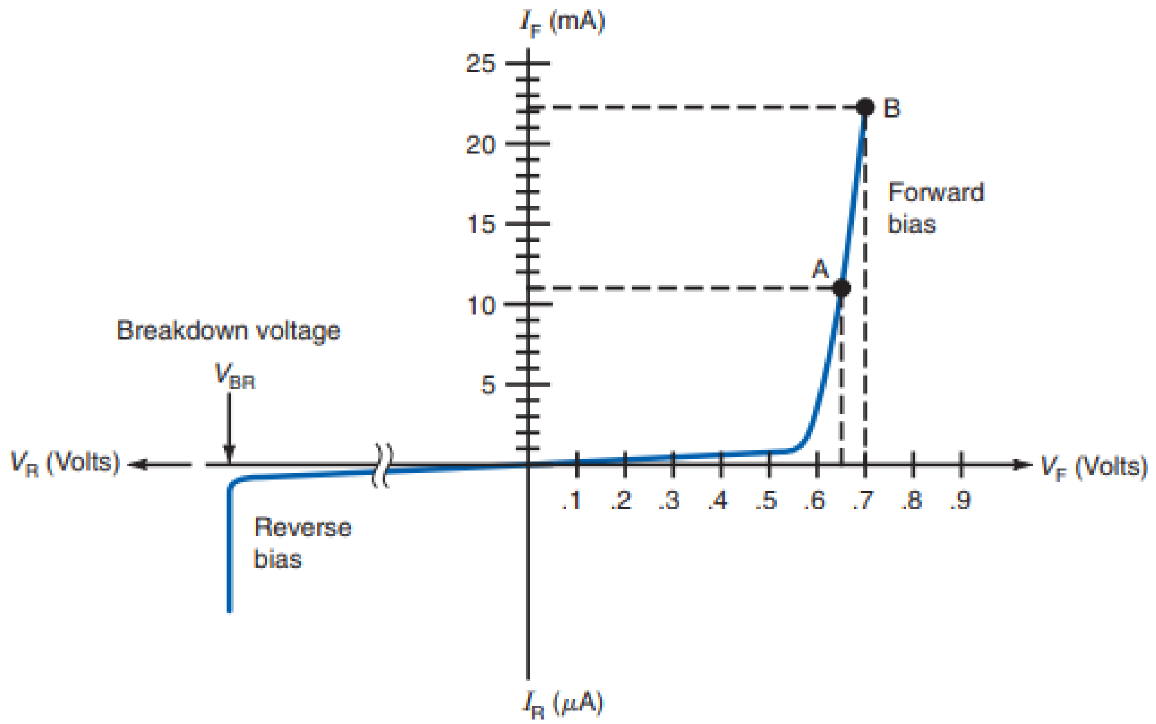
Figure 5 is a graph of diode current versus diode voltage for a silicon diode. The graph includes the diode current for both forward- and reverse-bias voltages. The upper right quadrant of the graph represents the forward-bias condition. Notice that very little diode current flows when the forward voltage, VF, is less than about 0.6 V. Beyond 0.6 V of forward bias, however, the diode current increases sharply. Notice that the forward voltage drop, VF, remains relatively constant as IF increases. A voltage of 0.7 V is the approximate value assumed for the barrier potential of a silicon p - n junction. The barrier potential of germanium diodes is approximately 0.3 V. Therefore, if the graph in Fig. 5 were for a germanium diode, the current would increase sharply for a forward voltage of about 0.3 V.



Diode Fundamentals

Breakdown Voltage, VBR

The lower left quadrant of the graph in Fig. 5 represents the reverse-bias condition. Notice that only a very small current flows until the breakdown voltage, VBR, is reached. The current that flows prior to breakdown is mainly the result of thermally produced minority current carriers. As mentioned earlier, this current is called leakage current and is usually designated IR. Leakage current increases mainly with temperature and is relatively independent of changes in reverse-bias voltage. The slight increase in reverse current, IR, with increases in the reverse voltage, VR, is a result of surface leakage current. Surface leakage current exists because there are many holes on the edges of a silicon crystal due to unfilled covalent bonds. These holes provide a path for a few electrons along the surfaces of the crystal.



Diode Fundamentals

Breakdown Voltage, VBR

Avalanche occurs when the reverse-bias voltage, VR, becomes excessive. Thermally produced free electrons on the p side are accelerated by the voltage source to very high speeds as they move through the diode. These electrons collide with valence electrons in other orbits. These valence electrons are also set free and accelerated to very high speeds, thereby dislodging even more valence electrons. The process is cumulative; hence, we have an avalanche effect. When the breakdown voltage, VBR, is reached, the reverse current, IR, increases sharply. Diodes should not be operated in the breakdown region. Most rectifier diodes have breakdown voltages exceeding 50 V.

Diode Fundamentals

DC Resistance of a Diode

Examine the forward-bias region of the graph shown in Fig. 5. The graph of VF versus IF shows that a diode is a nonlinear device because the diode current, IF, does not increase in direct proportion to the diode voltage, VF.

For example, the diode voltage does not have to be doubled to double the diode current. The dc resistance of a forward-biased diode can be calculated using Formula (1).

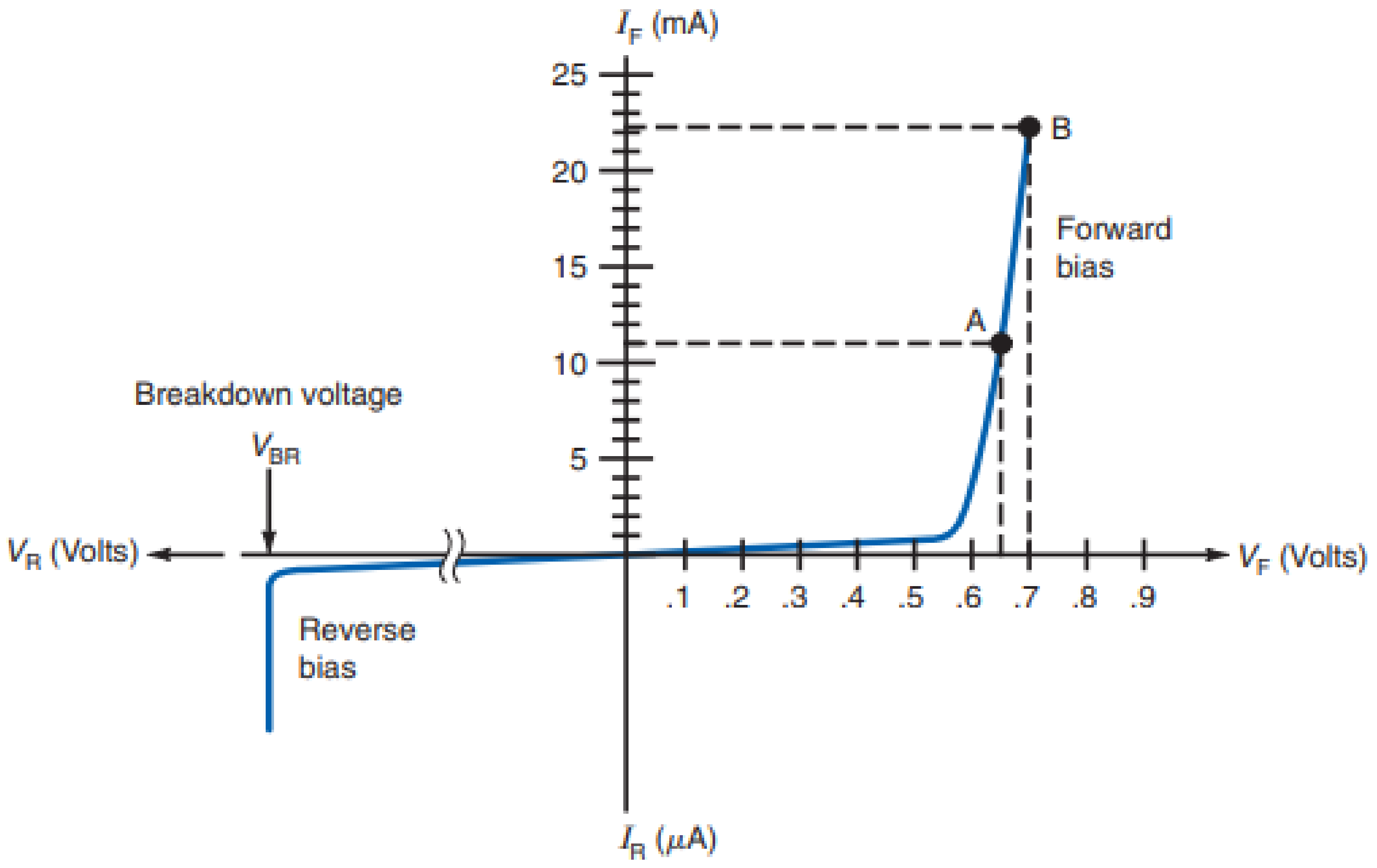
$$R_F = \frac{V_F}{I_F}$$

where VF is the forward voltage drop and IF is the forward current.

Diode Fundamentals

Sample Problems

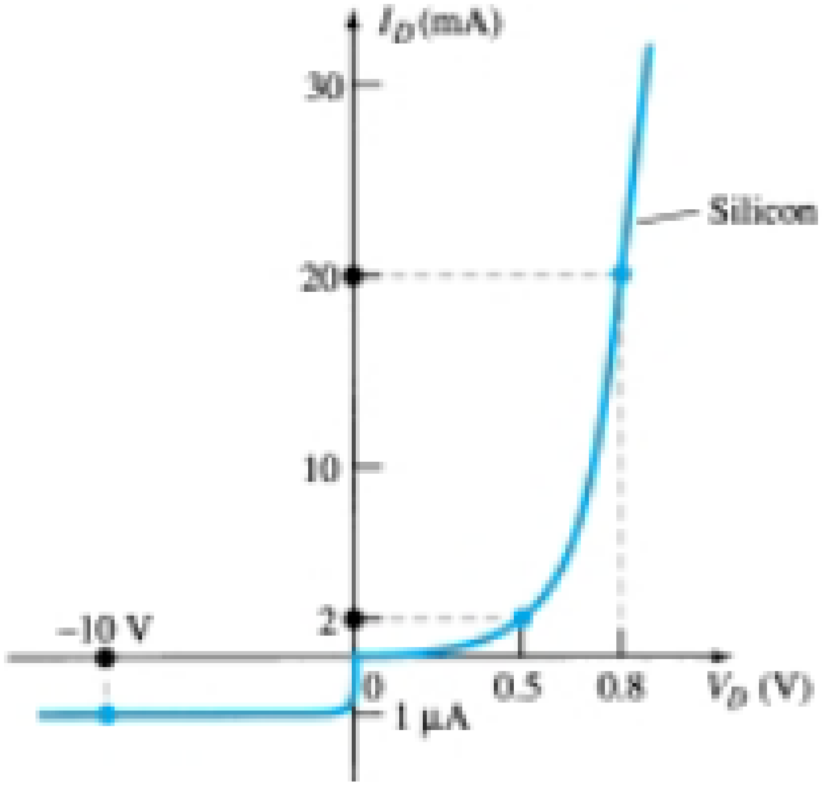
For the diode curve in Fig. 5, calculate the dc resistance, RF, at points A and B.



Diode Fundamentals

Sample Problems

Determine the dc resistance levels for the diode of the figure shown if (a) IF = 2mA,(b) IF = 20mA and (c) VF = -10V



Diode Fundamentals

Try It Yourself!

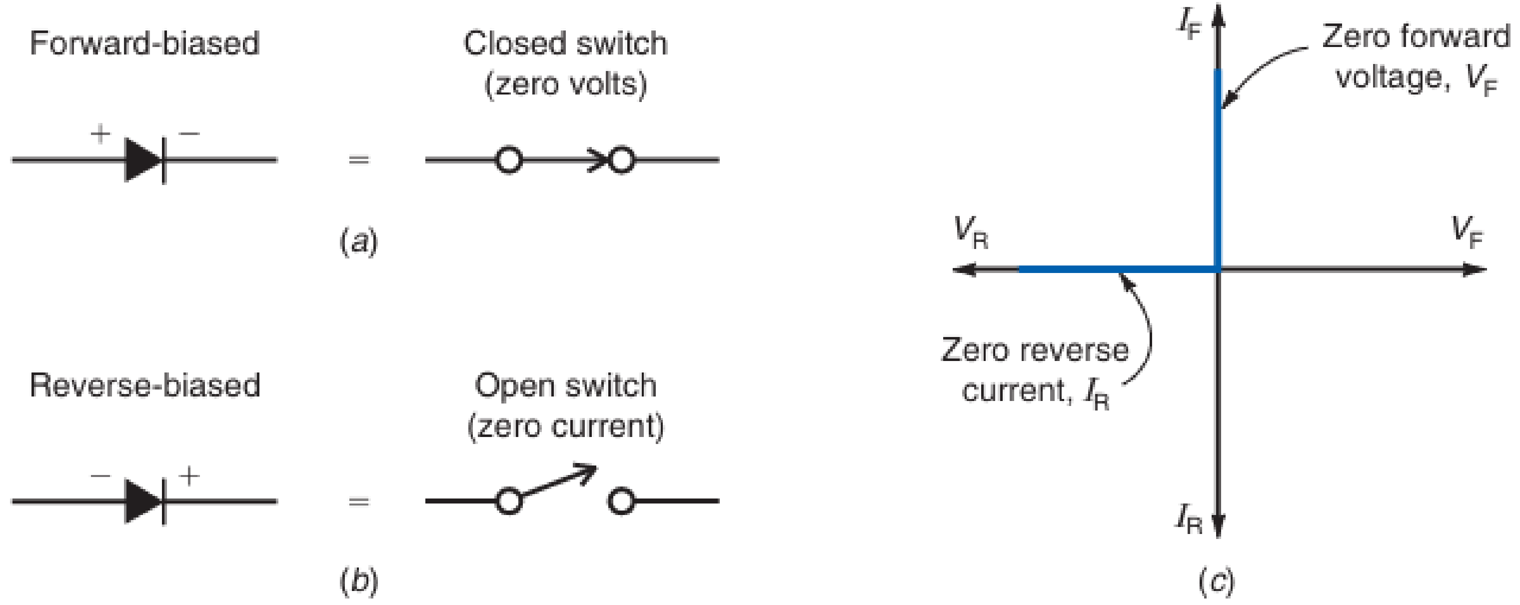
Calculate the dc resistance of a diode for the following values of VF and IF:

a. VF = 0.5 V, IF = 50 μA.
b. VF = 0.55 V, IF = 500 μA.
c. VF = 0.6 V, IF = 1 mA.

Diode Approximations

First Approximation

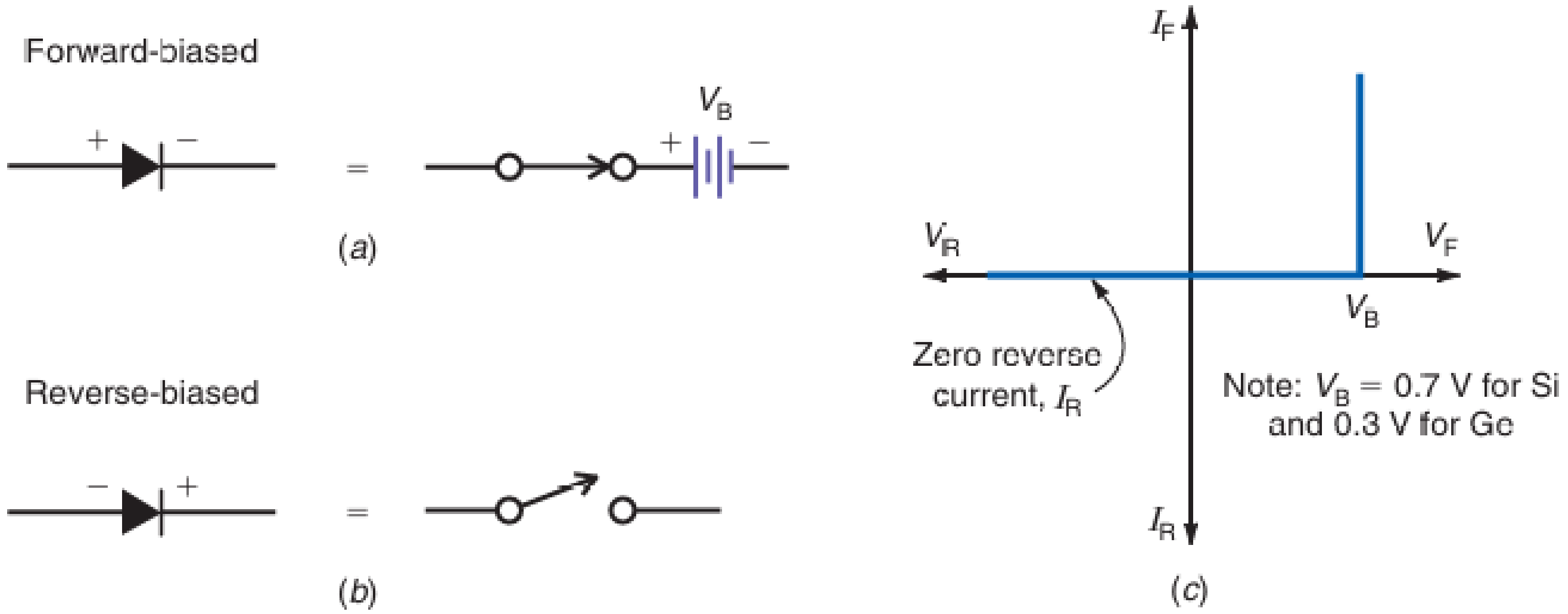
The first approximation treats a forward-biased diode like a closed switch with a voltage drop of zero volts, as shown in Fig. 6a. Likewise, the first approximation treats a reverse-biased diode like an open switch with zero current, as shown in Fig. 6b. The graph in Fig. 6c indicates the ideal forward- and reverse-bias characteristics. The first approximation of a diode is often used if only a rough idea is needed of what the circuit voltages and currents should be. The first approximation is sometimes called the ideal diode approximation.



Diode Approximations

Second Approximation

The second approximation treats a forward-biased diode like an ideal diode in series with a battery, as shown in Fig. 7a. For silicon diodes, the battery voltage is assumed to be 0.7 V, the same as the barrier potential, VB, at a silicon p - n junction. The second approximation of a reverse-biased diode is an open switch. See Fig. 7b . The graph in Fig. 7c indicates the forward- and reverse-bias characteristics of the second approximation. Notice that the diode is considered off until the forward voltage, VF, reaches 0.7 V. Also, the diode is assumed to drop 0.7 V for all currents that pass through it. The second approximation is used if more accurate answers are needed for circuit calculations.

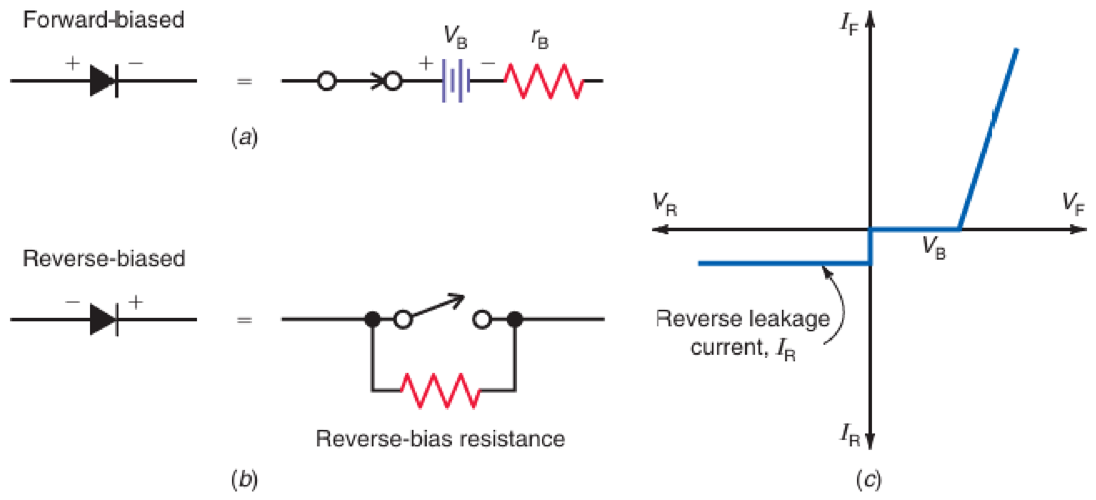


Diode Approximations

Third Approximation

The third approximation of a diode includes the bulk resistance, designated rB. The bulk resistance, rB, is the resistance of the p and n materials. Its value is dependent on the doping level and the size of the p and n materials. The third approximation of a forward-biased diode is shown in Fig. 8a. The total diode voltage drop using the third approximation is calculated using Formula (2).

$$V_F = V_B + I_F r_B$$



The bulk resistance, rB, causes the forward voltage across a diode to increase slightly with increases in the diode current. Figure 8b shows the third approximation of a reverse-biased diode. The resistance across the open switch illustrates the high leakage resistance for the reverse-bias condition. Notice the small leakage current in the graph of Fig. 8c when the diode is reverse-biased. This is a result of the high resistance that exists when the diode is reverse-biased.

Diode Approximations

Bulk Resistances

The graph in Fig. 8c shows the forward- and reverse-bias characteristics included with the third approximation. Notice the slope of the diode curve when forward-biased. The value of the bulk resistance, rB, can be determined by using Formula (3).

$$r_B = \frac{\Delta V}{\Delta I}$$

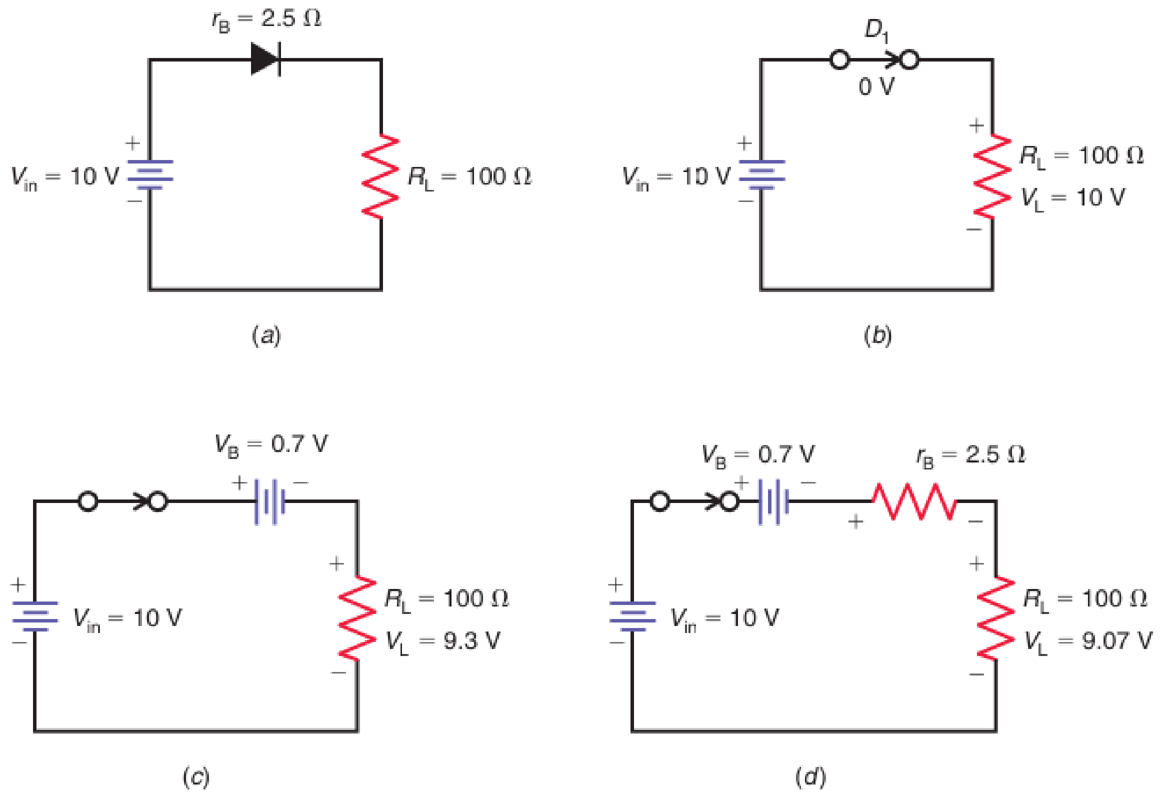
where ΔV represents the change in diode voltage produced by the changes in diode current, ΔI.

Diode Approximations

Sample Problems

A silicon diode has a forward voltage drop of 1.1 V for a forward diode current, IF, of 1 A. Calculate the bulk resistance, rB.

In Figure shown below, solve for the load voltage and current using the first, second, and third diode approximations.

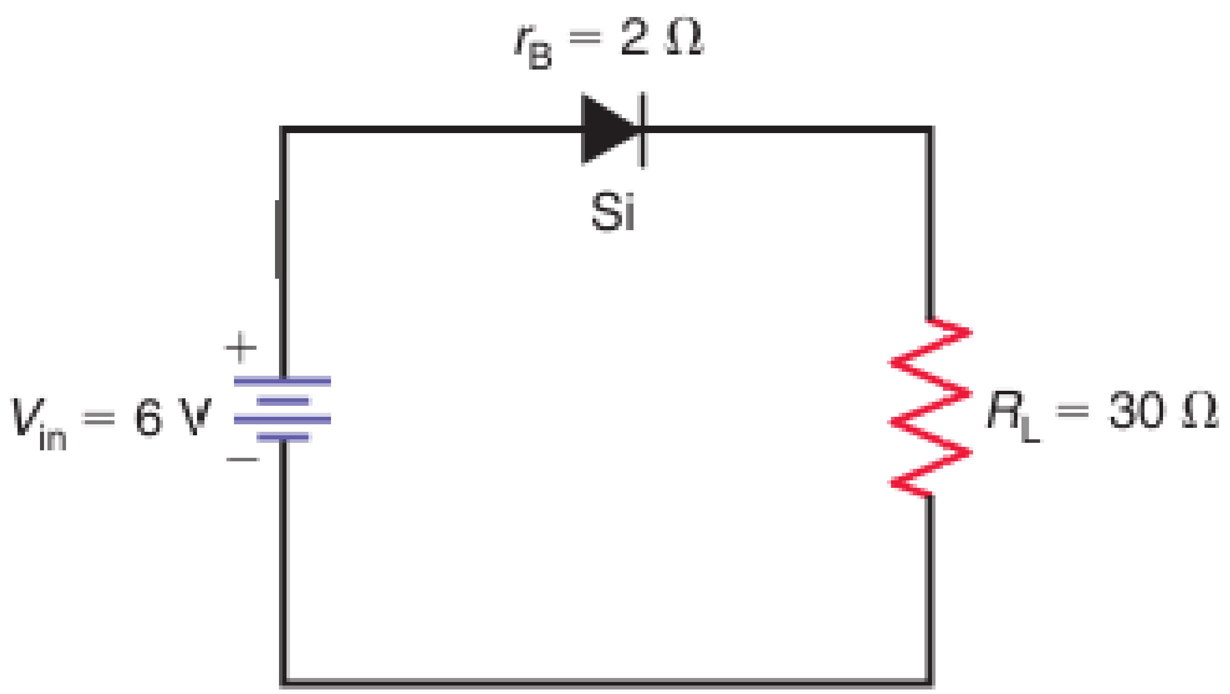


Diode Approximations

Try It Yourself!

What is the bulk resistance of a silicon diode for each of the following sets of values: when VF = 0.8 V, IF = 100 mA and when VF = 0.72 V, IF = 40 mA?

In the Figure shown below, how much is the total diode drop when the third approximation is used to solve for VL and IL?



Special Diodes: Light Emitting Diodes

When elements such as gallium, arsenic, and phosphorus are used in doping, a manufacturer can make diodes that emit different colors of light. These diodes are called light-emitting diodes(LEDs). Some common LED colors are red, green, yellow, orange, and even infrared (invisible) light. LEDs now operate in place of incandescent lamps in many cases. A semitransparent material is used with LEDs so that light can escape and be visible.

How It Happens?

For any diode that is forward-biased, free electrons and holes combine at the junction. When free electrons from the n side cross over into the p side, they fall into a hole. When an electron falls, it releases energy. This energy is mainly heat or light. For the normal silicon diode, the light cannot escape because the device is not transparent. Because LEDs use a semitransparent material, however, light can escape to the surrounding environment. The color of the light emitted from the LED depends on the type of element used in the manufacture of the LED.

Special Diodes: Light Emitting Diodes

LED Characteristics

A light-emitting diode is represented using the schematic symbol shown in Fig. 9. The arrows pointing outward indicate the emitted light with forward bias. The internal barrier potential, VB, for an LED is considerably higher than that of an ordinary silicon diode. Typical values of VB for an LED range from approximately 1.5 to 2.5 V. The exact amount of forward voltage drop varies with the color of the LED and also with the forward current through the LED. In most cases, the LED voltage drop can be assumed to be 2.0 V for all LED colors and all values of forward current. This is a convenient value to use in troubleshooting and design.

Special Diodes: Light Emitting Diodes

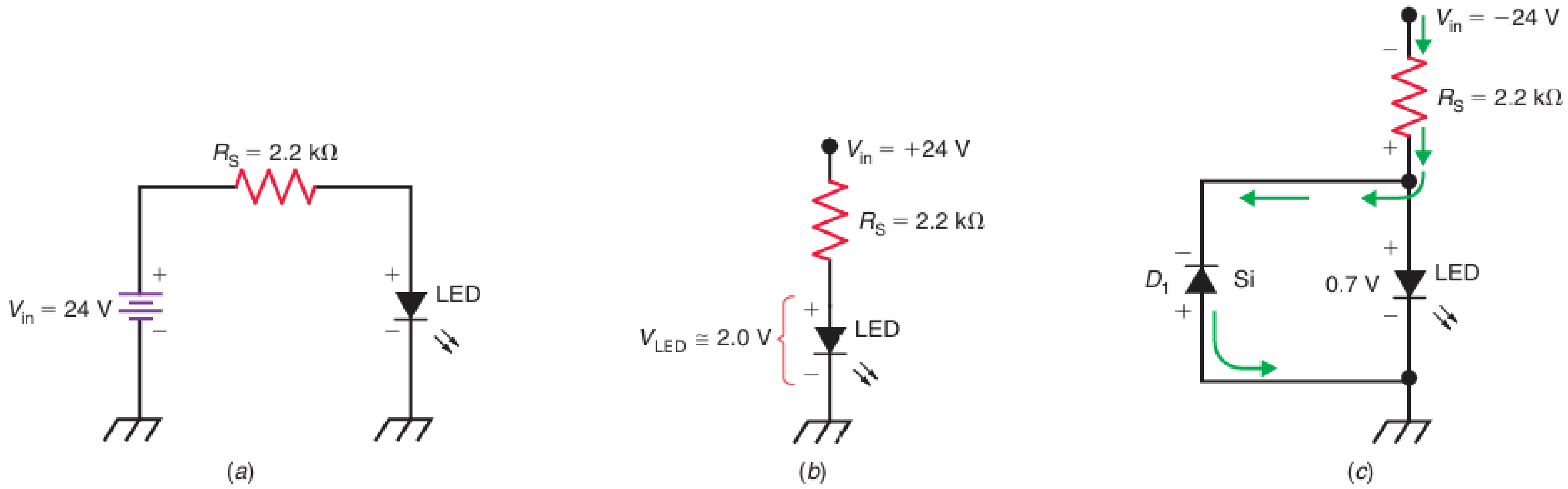
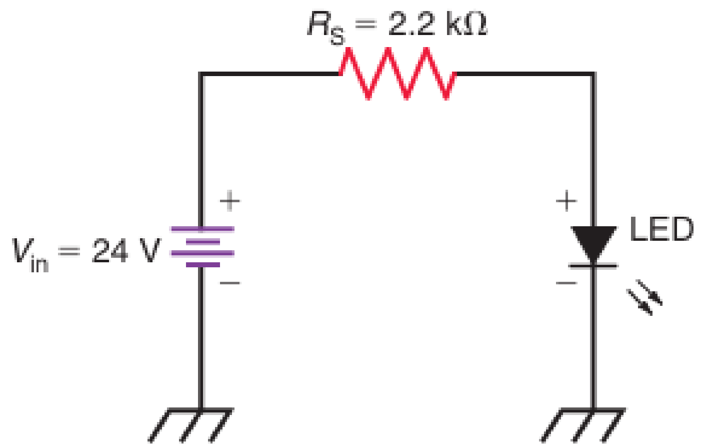


Figure 10b shows how the circuit of Fig. 10a is normally drawn in commercial schematics. It is common practice to show only the potential difference and its polarity with respect to chassis ground.

Special Diodes: Light Emitting Diodes

Sample Problems

Calculate the LED current in Figure 10a.

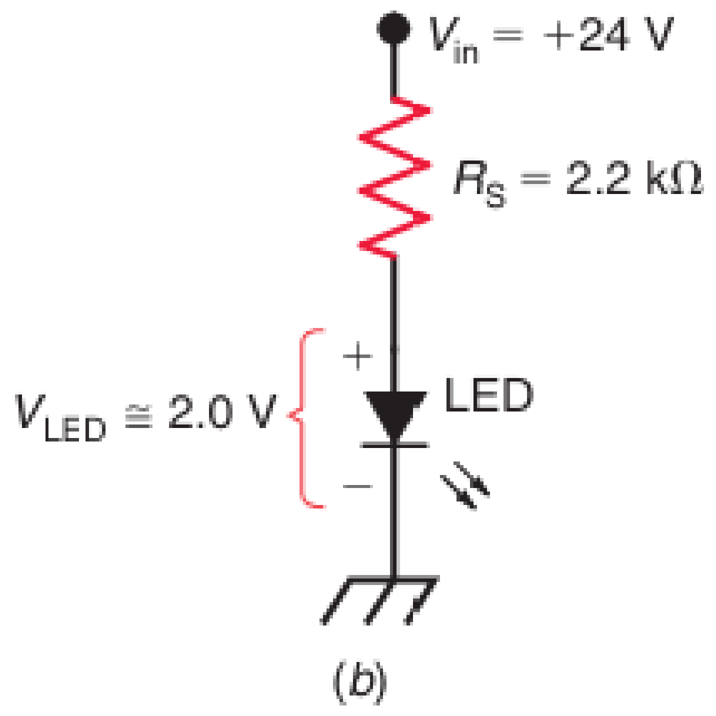


(a)

Special Diodes: Light Emitting Diodes

Sample Problems

In Figure 10b, calculate the resistance, RS, required to provide an LED current of 25 mA.



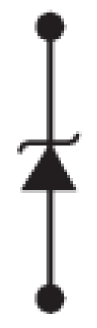
Special Diodes: Light Emitting Diodes

Breakdown Voltage Rating, VBR

LEDs have a very low breakdown voltage rating. Typical values of VBR range from 3 to 15 V. Because of the low value of breakdown voltage, accidentally applying even a small value of reverse voltage can destroy the LED or severely degrade its performance. One way to protect an LED against excessive reverse voltage is to connect a silicon diode in parallel with the LED, as shown in Fig. 10c. The parallel connection ensures that the LED cannot accidentally receive a reverse-bias voltage greater than its breakdown voltage rating, VBR . In this case, the LED has a maximum reverse voltage, VR, equal to the forward voltage of 0.7 V across D1. Note that a negative voltage would never be intentionally applied to the circuit shown in Fig. 10c. The negative value of 24 V for Vin represents an accidental application of negative voltage caused by a fault in the power supply circuit that provides power for the LED.

Special Diodes: Zener Diodes

A zener diode is a special diode that has been optimized for operation in the breakdown region. These devices are unlike ordinary rectifier diodes, which are never intended to be operated at or near breakdown. Voltage regulation is the most common application of a zener diode. The zener diode is connected in parallel with the load of the power supply. The zener voltage remains constant despite load current variations. Figure 11a shows the schematic symbol of a zener diode.

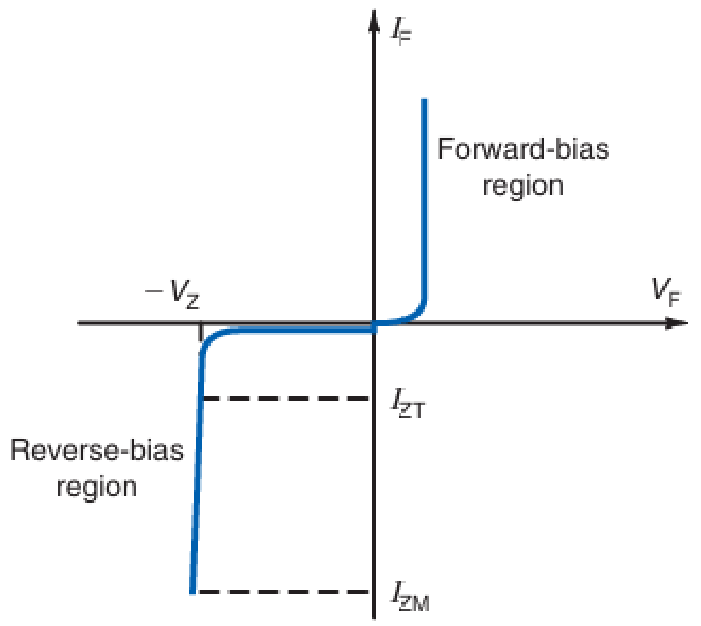


(a)

Special Diodes: Zener Diodes

Volt-Ampere Characteristic Curve

Figure 11b shows the volt-ampere characteristic curve for a typical silicon zener diode. In the forward region, the zener acts like an ordinary silicon rectifier diode with a forward voltage drop of about 0.7 V when conducting. In the reverse-bias region, a small reverse leakage current flows until the break down voltage is reached. At this point, the reverse current through the zener increases sharply. The reverse current is called zener current, designated IZ. Notice that the breakdown voltage, designated -VZ, remains nearly constant as the zener current, IZ, increases. Because of this characteristic, a zener diode can be used in voltage regulation circuits, since the zener voltage, VZ, remains constant even though the zener current, IZ, varies over a wide range. Most manufacturers specify the zener voltage, VZ, at a specified test current designated IZT. For example, a 1N4742A zener diode has a rated zener voltage, VZ, of 12.0 V for a test current, IZT, of 21 mA. The suffix A in the part number 1N4742A indicates a zener voltage tolerance of 5%.



(b)

Special Diodes: Zener Diodes

Zener Ratings

An important zener rating is its power rating. In terms of power dissipation,

$$P_Z = V_Z I_Z$$

where PZ equals the power dissipated by the zener, VZ equals the zener voltage, and IZ equals the zener current.

The power dissipation in a zener diode must always be less than its power dissipation rating. The power rating of a zener is designated PZM. The maximum current that a zener can safely handle is given in Formula (4):

$$I_{ZM} = \frac{P_{ZM}}{V_Z}$$

where VZ equals the zener voltage, IZM equals the maximum-rated zener current, and PZM equals the power rating of the zener. IZM is shown on the graph in Fig. 11b. Exceeding the value of IZM will burn out the zener.

Special Diodes: Zener Diodes

Sample Problem

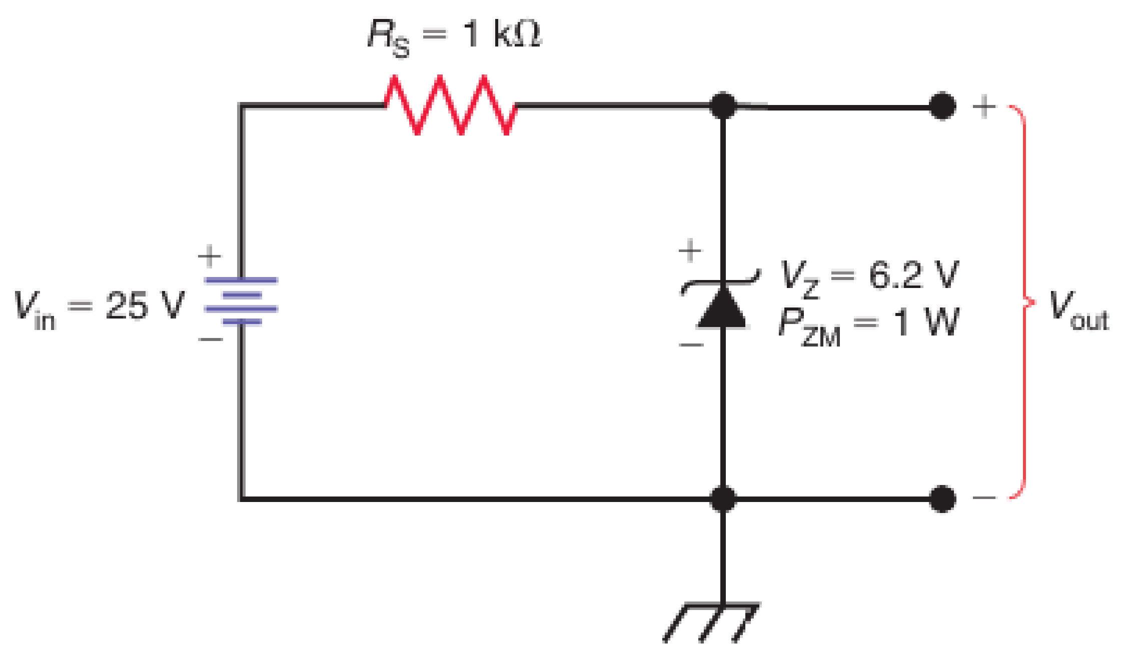
Calculate the maximum-rated zener current for a 1-W, 10-V zener.

Special Diodes: Zener Diodes

Zener Diode Applications

Figure 12 shows an unloaded voltage regulator that uses a 6.2-V zener diode. Notice that the zener diode is reverse-biased with the positive terminal of Vin connected to the cathode of the zener diode through the series limiting resistor, RS. The zener diode provides an output voltage of 6.2 V. The zener current is calculated by dividing the voltage across the series resistor, RS, by the value of RS. The calculations are

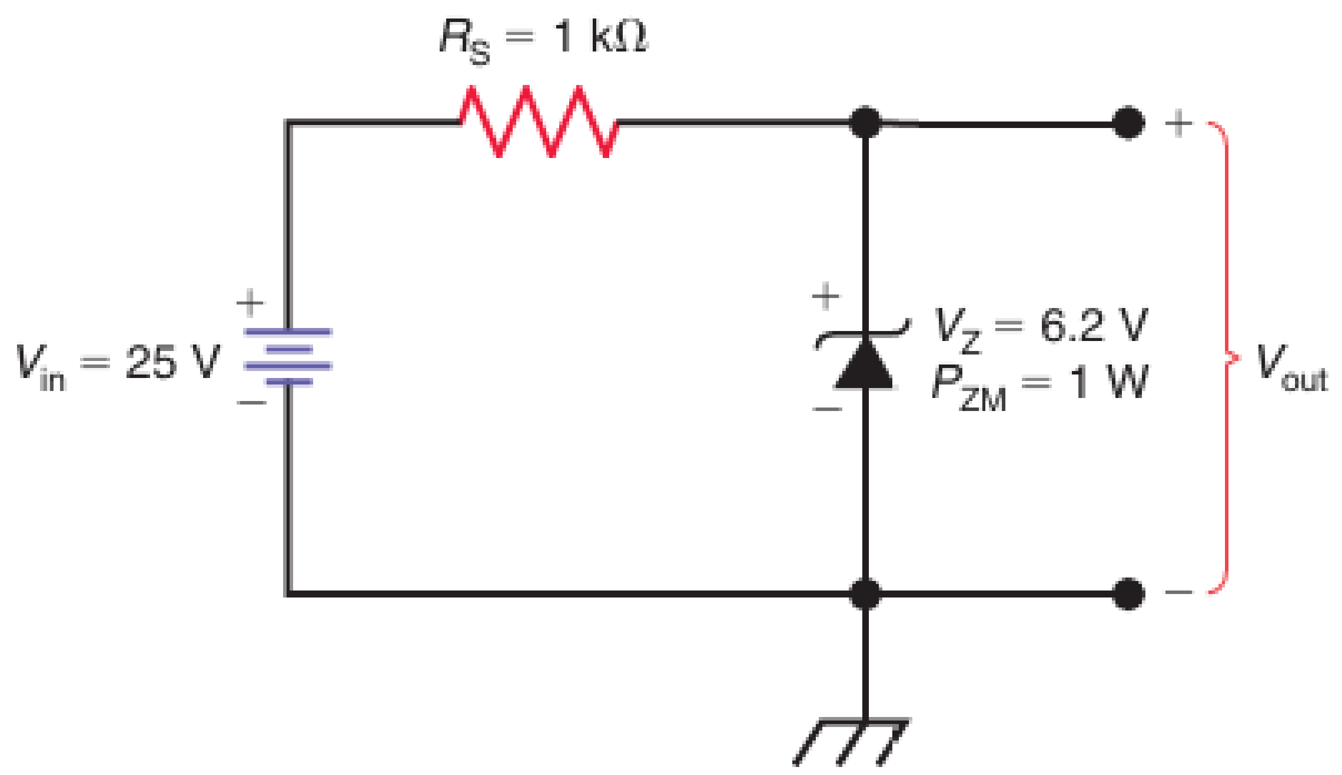
$$I_Z = \frac{V_{in} - V_Z}{R_S}$$



Special Diodes: Zener Diodes

Sample Problem

If VZ = 10 V in Fig. 12, calculate IZ.

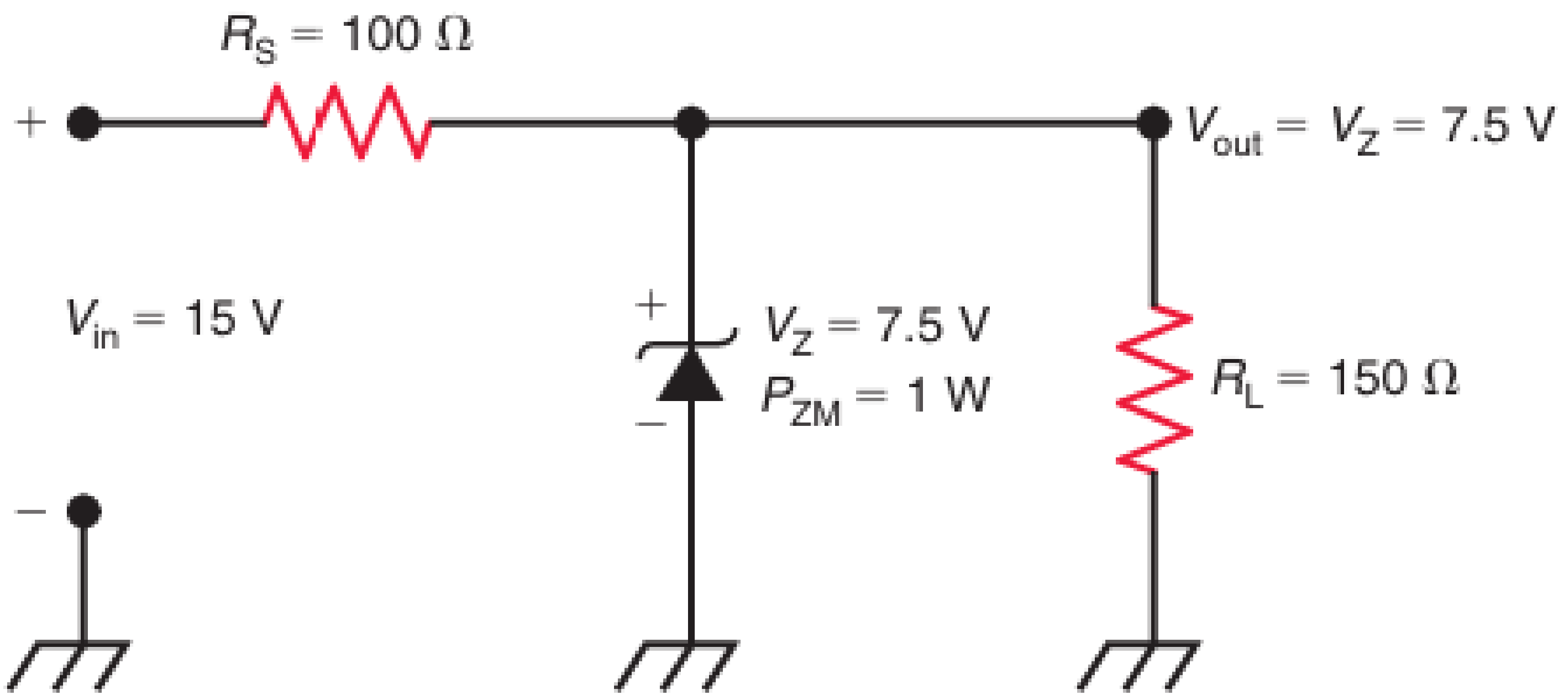


Special Diodes: Zener Diodes

Loaded Zener Regulators

The unloaded voltage regulator shown in Fig. 12 has few applications in electronics. Usually, a load resistor is connected across the output, as shown in Fig. 13. This is a typical loaded voltage regulator. Since RL is across the zener, the load voltage equals the zener voltage, or VL = VZ . It is important to note in Fig. 13 that the voltage dropped across the series resistor, RS, is Vin – VZ. Thus, the current, IS, through the series resistor is calculated as

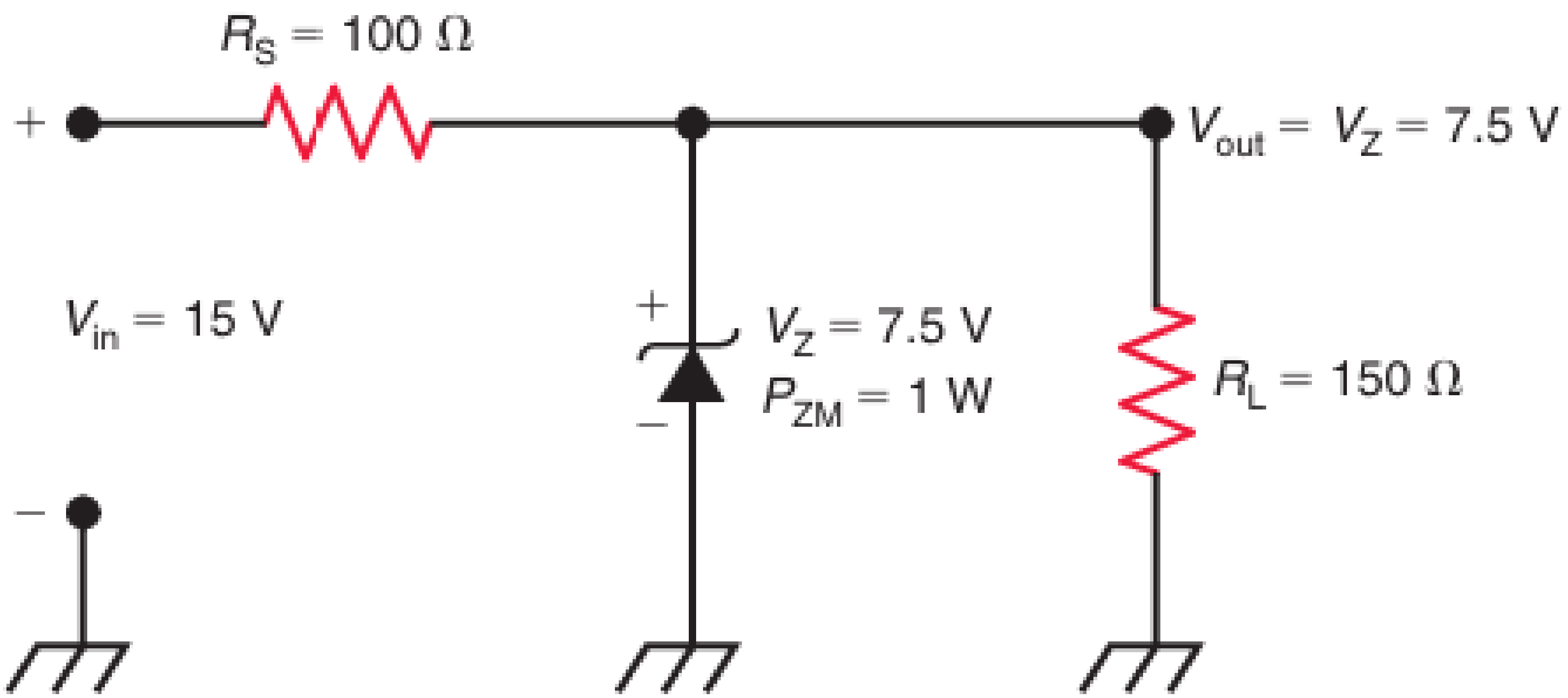
$$I_S = \frac{V_{in} - V_Z}{R_S}$$



Special Diodes: Zener Diodes

Sample Problems

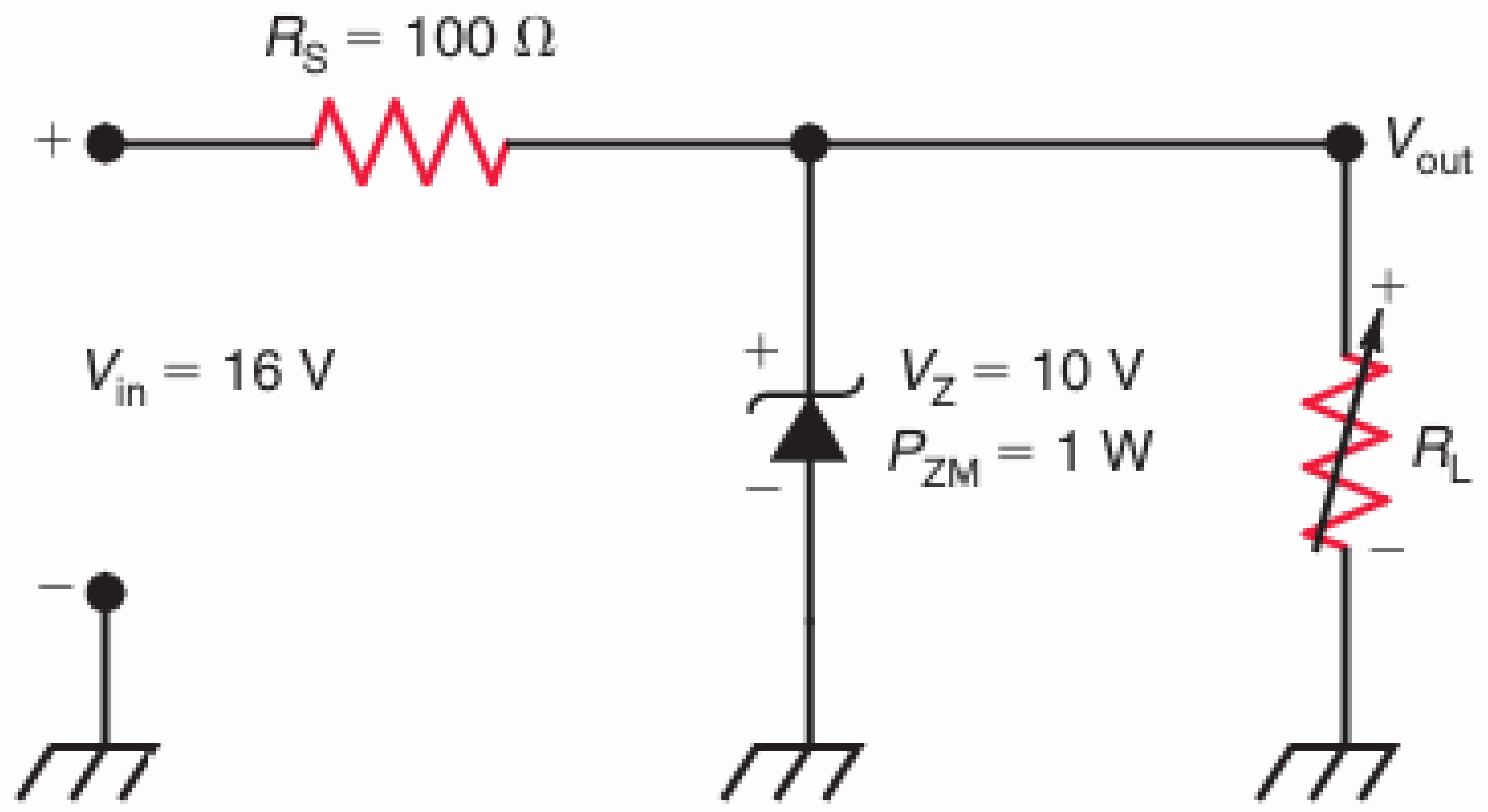
If RL increases to 250Ω in Fig. 13, calculate the following: IS, IL, IZ, and PZ.



Special Diodes: Zener Diodes

Sample Problems

In the Figure shown below, calculate IS, IL, and IZ for (a) RL 200Ω ; (b) RL 500Ω.



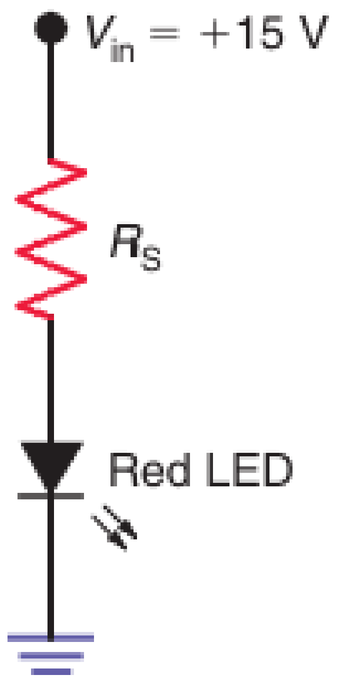
Special Diodes: Light Emitting Diodes

Try It Yourself!

In the Figure shown below, calculate the LED current for each of the following values of RS:

a. RS = 2.7 kΩ.

b. RS = 1.5 kΩ.



Special Diodes: Light Emitting Diodes

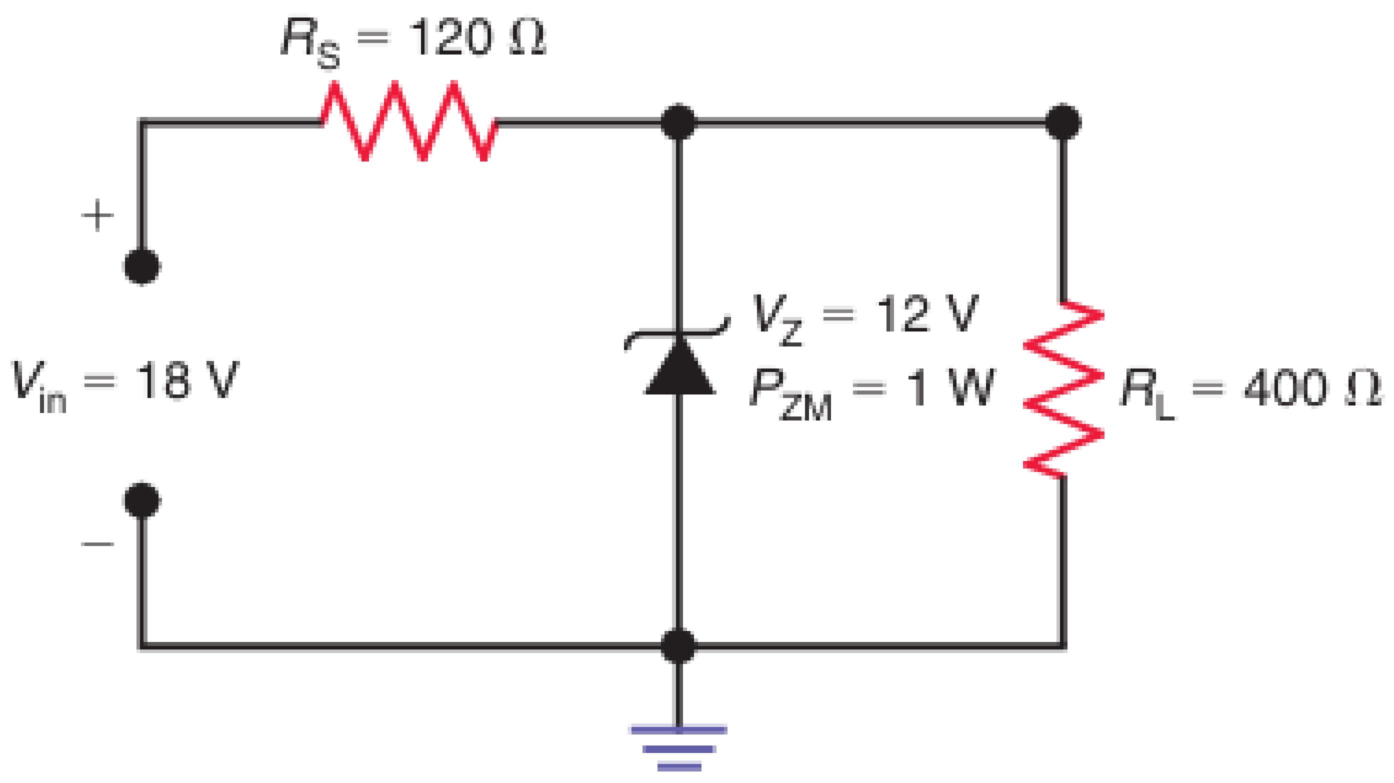
Try It Yourself!

In the Figure shown below, solve for the following:

a. IS.

b. IL.

c. IZ.



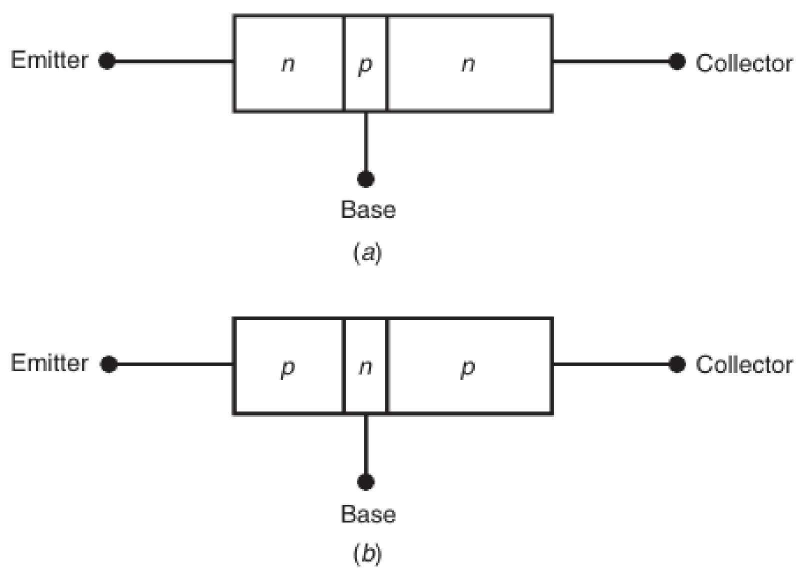
Bipolar Junction Transistor

Transistors are used when it is necessary to amplify voltage, current, and power. With a small signal applied to the transistor amplifier, the transistor and its associated circuitry can produce an amplified version of the input signal. The output signal can be hundreds or even thousands of times larger than the input signal. In computer circuits, the transistor can be used as an electronic switch.

Bipolar Junction Transistor

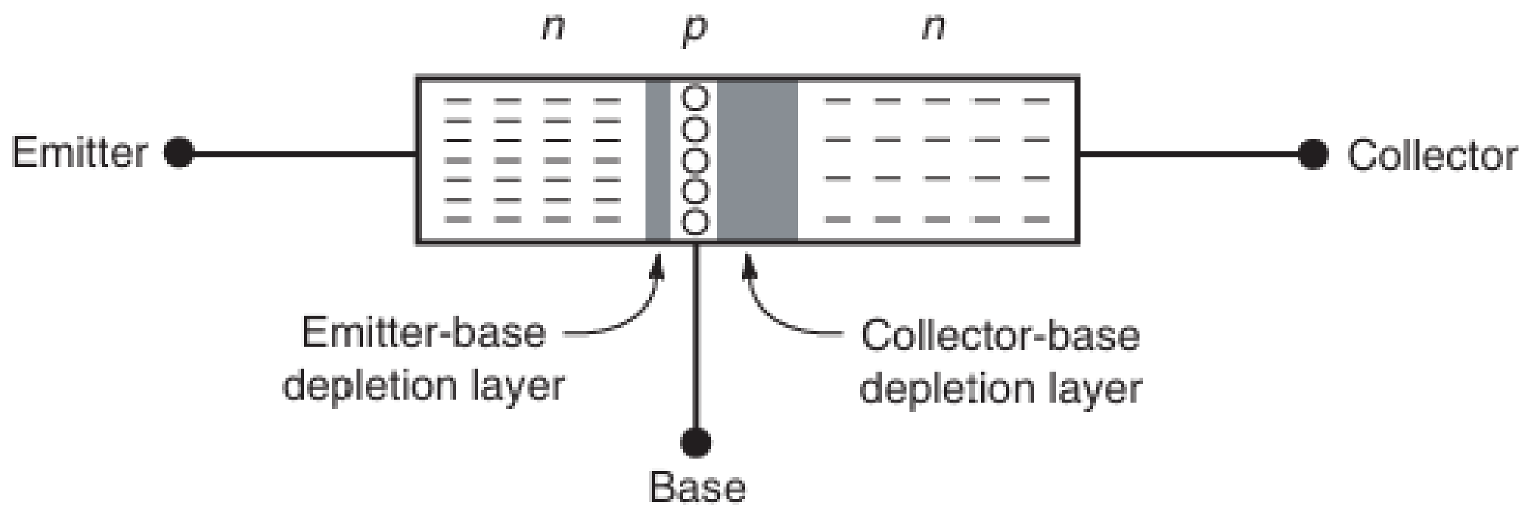
Transistor Construction

A transistor has three doped regions, as shown in Fig. 14. Figure 14a shows an npn transistor, and Fig. 14b shows a pnp transistor. Notice that for both types, the base is a narrow region sandwiched between the larger collector and emitter regions. The emitter region of a transistor is heavily doped. Its job is to emit or inject current carriers into the base. The base region is very thin and lightly doped. Most of the current carriers injected into the base from the emitter do not flow out the base lead. Instead, most of the current carriers injected into the base pass on to the collector. The collector region is moderately doped and is the largest of all three regions. The collector region attracts the current carriers that are injected into the thin and lightly doped base region. Incidentally, the collector region is the largest of all three regions because it must dissipate more heat than the emitter or base regions.



Bipolar Junction Transistor

In npn transistors, the majority current carriers are free electrons in the emitter and collector, whereas the majority current carriers are holes in the base. The opposite is true in a pnp transistor where the majority current carriers are holes in the emitter and collector, and the majority current carriers are free electrons in the base. Figure 15 shows the depletion layers in an unbiased npn transistor. The diffusion of electrons from both n regions into the p -type base causes a barrier potential, VB, for both p-n junctions. The p-n junction at the left is the emitter-base junction; the p-n junction at the right is the collector-base junction. For silicon, the barrier potential for both the emitter-base (EB) and collector-base (CB) junctions equals approximately 0.7 V.



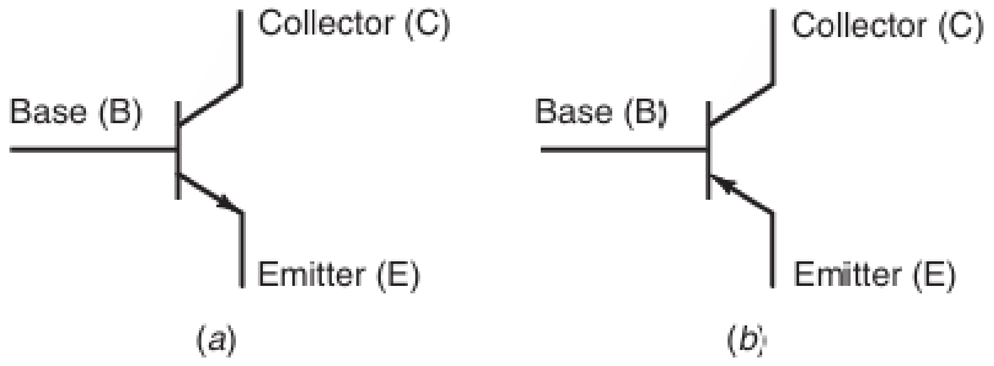
Bipolar Junction Transistor

Notice in Fig. 15 that the EB depletion layer is narrower than the CB depletion layer. The reason for the different widths can be attributed to the doping level of the emitter and collector regions. With heavy doping in the emitter region, the penetration into the n material is minimal due to the availability of many free electrons. On the collector side, however, there are fewer free electrons available due to the more moderate doping level in this region. Therefore, the depletion layer must penetrate deeper into the collector region to set up the barrier potential, VB, of 0.7 V. In Fig. 15 dash marks are used in the n -type emitter and collector to indicate the large number of free electrons in these regions. Small circles are used to indicate the holes in the p -type base region. (For an npn transistor, holes are the minority current carriers in the n -type emitter and collector regions, whereas free electrons are the minority current carriers in the p -type base.)

Bipolar Junction Transistor

Schematic Symbols

Figure 16 shows the schematic symbols for both the npn and pnp transistors. Notice the arrow on the emitter lead for both types. For the npn transistor in Fig. 16a, the arrow on the emitter lead points outward, and in the pnp transistor of Fig. 16b , the arrow on the emitter lead points inward. The npn and pnp transistors are not different in terms of their ability to amplify voltage, current, or power. Each type, however, does require different polarities of operating voltages. For example, the collector-emitter voltage, VCE, of an npn transistor must be positive, and the collector-emitter voltage, VCE, must be negative for the pnp type.



Bipolar Junction Transistor

In summary, it is important to note the following points about the construction of a transistor.

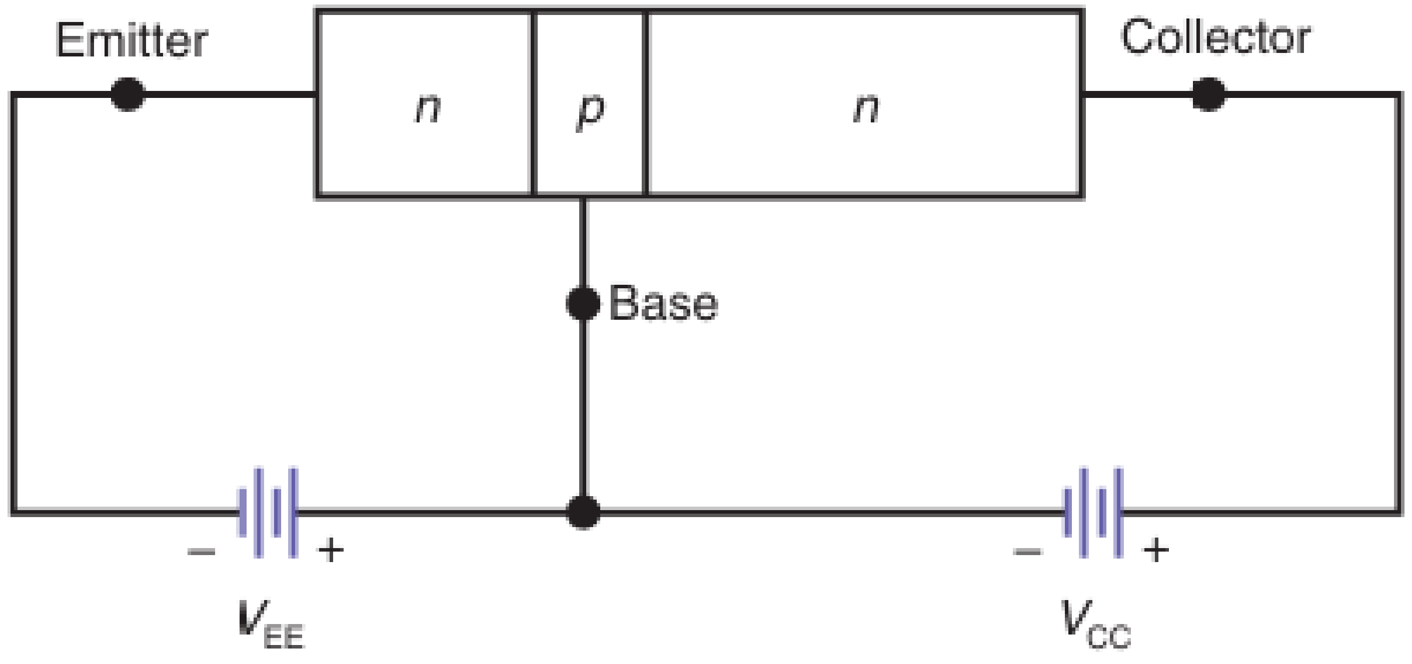
1. The emitter region is heavily doped. Its job is to emit or inject current carriers into the base region. For npn transistors, the n -type emitter injects free electrons into the base. For pnp transistors, the p -type emitter injects holes into the base.

2. The base is very thin and lightly doped. Most of the current carriers injected into the base region cross over into the collector side and do not flow out the base lead.

3. The collector region is moderately doped. It is also the largest region within the transistor. Its function is to collect or attract current carriers injected into the base region.

Proper Transistor Biasing

For a transistor to function properly as an amplifier, the emitter-base junction must be forward-biased, and the collector-base junction must be reverse-biased, as illustrated in Fig. 17a. Notice the common connection for the voltage sources at the base lead of the transistor. The emitter-base supply voltage is designated VEE and the collector-base supply voltage is designated VCC.

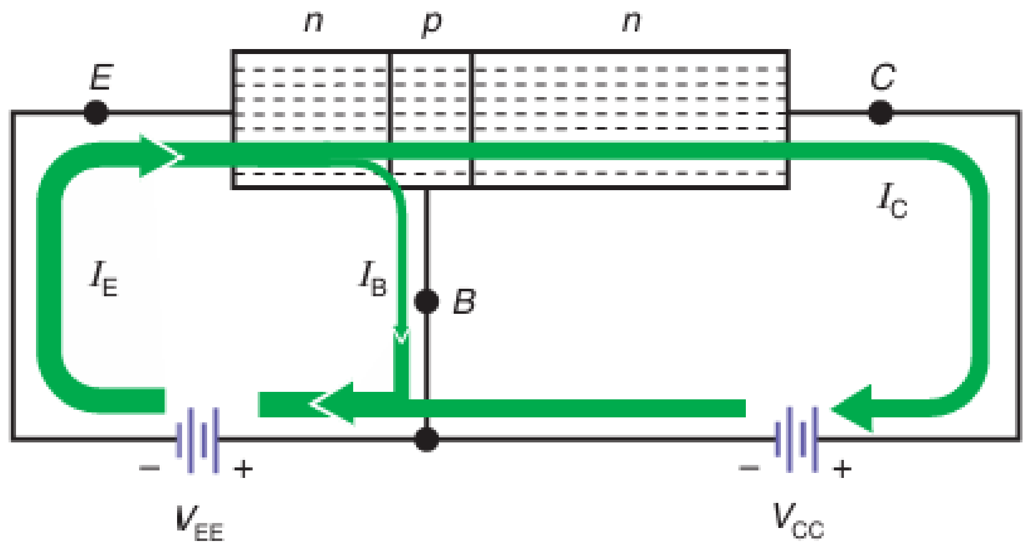


(a)

Proper Transistor Biasing

Transistor Currents

Figure 17b shows the emitter current, IE, the base current, IB, and the collector current, IC. Electrons in the n -type emitter are repelled into the base by the negative terminal of the emitter supply voltage, VEE. Since the base is very thin and lightly doped, only a few electrons combine with holes in the base. The small current flowing out of the base lead (which is the base current, IB) is called recombination current because free electrons injected into the base must fall into a hole before they can flow out the base lead.



(b)

Proper Transistor Biasing

Notice in Fig. 17b that most of the emitter-injected electrons pass through the base region and into the collector region. The reason is two-fold. First, only a few holes are available for recombination in the base. Second, the positive collector-base voltage attracts the free electrons in the p -type base over to the collector side before they can recombine with holes in the base. In most transistors, the collector current, IC, is nearly identical to the emitter current, IE. This is equivalent to saying that the recombination current, IB, is very small. Only a small voltage is needed to create an electric field strong enough in the collector-base junction to collect almost all free electrons injected into the base. After the collector-base voltage reaches a certain level, increasing it further will have little or no effect on the number of free electrons entering the collector. As a matter of fact, after the collector-base voltage is slightly above zero, full current is obtained in the collector. If the voltage across the collector-base junction is too large, how ever, the breakdown voltage may be exceeded, which could destroy the transistor. Notice the relative size of the current arrows shown in Fig. 17b. The currents are illustrated in this manner to emphasize their relationship with each other. The currents in a transistor are related as shown in Formulas (5), (6), and (7).

$$I_E = I_B + I_C$$

$$I_C = I_E - I_B$$

$$I_B = I_E - I_C$$

Proper Transistor Biasing

Sample Problems

A transistor has the following currents: I_B = 20 mA and I_C = 4.98 A. Calculate I_E.

A transistor has the following currents: I_E = 100 mA and I_B = 1.96 mA. Calculate I_C.

A transistor has the following currents: I_E = 50 mA and I_C = 49 mA. Calculate I_B.

Proper Transistor Biasing

Try It Yourself!

Solve for the unknown transistor current in each of the following cases:

a. I_E = 1 mA, I_B = 5 μA, I_C = ?

b. I_B = 50 μA, I_C = 2.25 mA, I_E = ?

c. I_C = 40 mA, I_E = 40.5 mA, I_B = ?

Proper Transistor Biasing

DC Alpha

The circuit shown in Fig. 17 is called a common-base(CB) connection because the base lead is common to both the input and output sides of the circuit. A characteristic that describes how closely the emitter and collector currents are in a common base circuit is called the dc alpha, designated αdc. This is expressed in Formula (8).

$$\alpha_{dc} = \frac{I_C}{I_E}$$

In most cases, the dc alpha is 0.99 or greater. The thinner and more lightly doped the base, the closer alpha is to one, or unity. In most cases, the dc alpha is so close to one that we ignore the small difference that exists.

Proper Transistor Biasing

Sample Problem

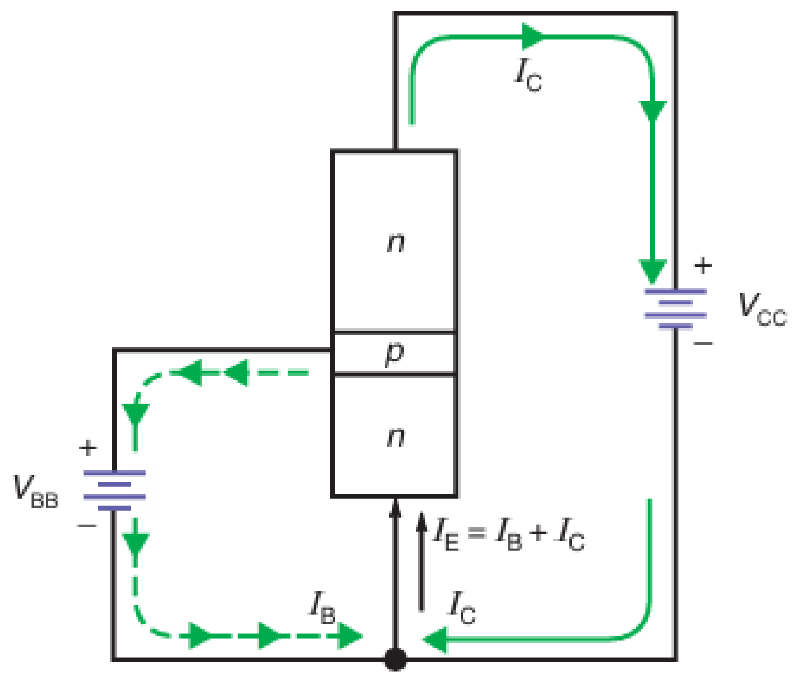
A transistor has the following currents: I_E = 15 mA, I_B = 60 μA Calculate α_{dc}.

Proper Transistor Biasing

DC Beta

Figure 18 shows another way to connect external voltages to the npn transistor. VBB provides the forward bias for the base-emitter junction, and VCC provides the reverse bias for the collector-base junction. This connection is called the common emitter (CE) connection since the emitter lead is common to both the input and output sides of the circuit. Notice the arrows indicating the direction of the transistor currents IE, IC, and IB. The dc current gain of a transistor in the common-emitter connection is called the dc beta, usually designated, βdc. The dc beta is expressed in Formula (9).

$$\beta_{dc} = \frac{I_C}{I_B}$$



Proper Transistor Biasing

Sample Problems

A transistor has the following currents: I_C = 10 mA, I_B = 50 μA. Calculate β_{dc} .

A transistor has β_{dc} = 150 and I_B = 75 μA . Calculate I_C.

Proper Transistor Biasing

Relating βdc and αdc

If βdc is known, αdc can be found by using Formula (10):

$$\alpha_{dc} = \frac{\beta_{dc}}{1 + \beta_{dc}}$$

Likewise, if αdc is known, βdc can be found by using Formula (11):

$$\beta_{dc} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}$$

These formulas are derived from Formulas (5), (6), and (7).

Proper Transistor Biasing

Sample Problems

A transistor has $\beta_{dc} = 100$. Calculate α_{dc} .

A transistor has $\alpha_{dc} = 0.995$. Calculate β_{dc} .

Proper Transistor Biasing

Try It Yourself!

A transistor has a base current, IB, of 15 μA. How much is the collector current, IC, if the transistor has a βdc of

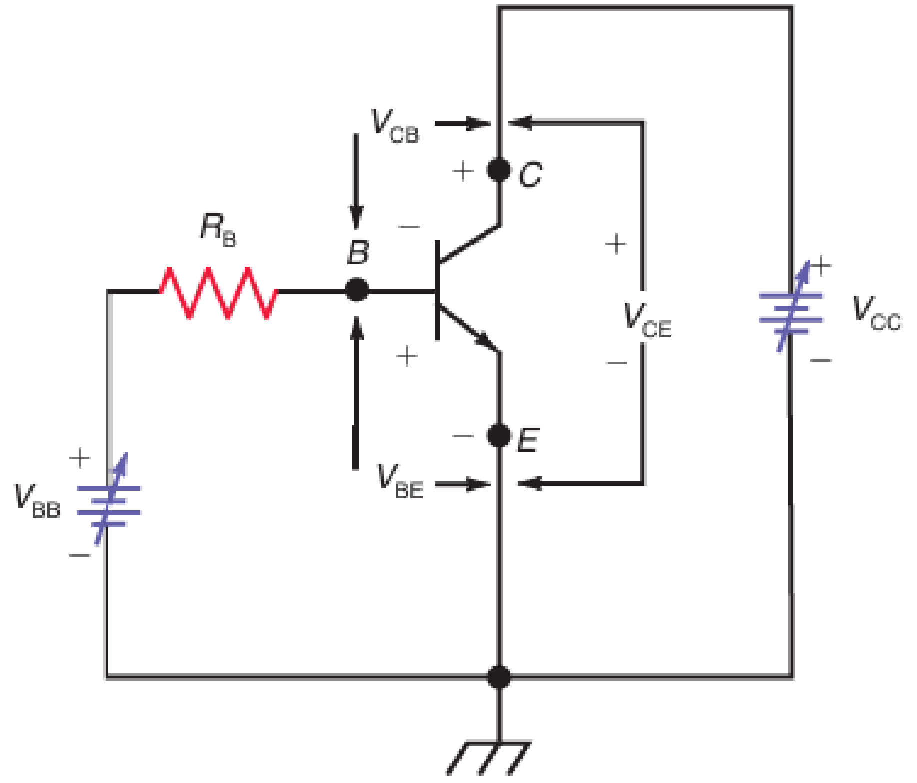
a. 50?
b. 100?
c. 150?

Calculate the dc alpha (αdc) for each of the following values of βdc:

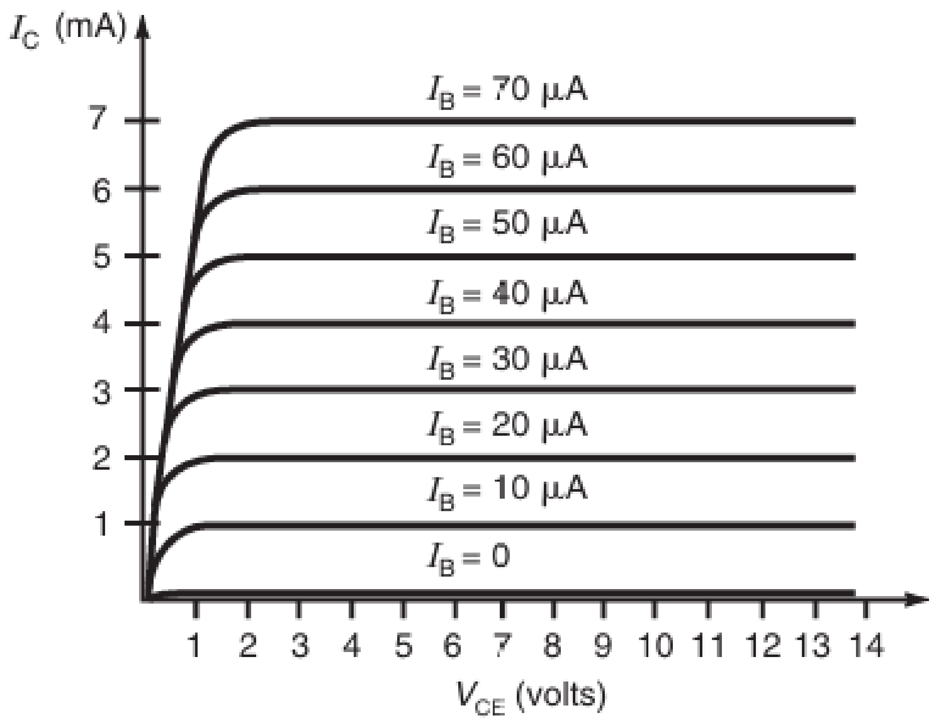
a. 50.
b. 125.
c. 250.

Transistor Operating Regions

Figure 19a shows an npn transistor in a CE connection. Notice that the base supply voltage, VBB, and the collector supply voltage, VCC, are variable. Notice also that a base resistor, RB, is used to control the amount of base current, IB. With a fixed value for RB, VBB can be adjusted to produce the desired value of base current.



(a)



(b)

Transistor Operating Regions

Transistor Voltages and Currents

In Fig. 19a, VBB can be adjusted to provide a wide range of base and collector current values. Assume that VBB has been adjusted to produce an IB of 50 μA. If βdc = 100, then IC is

$$
\begin{aligned}
I_C &= \beta_{dc} \times I_B \\
&= 100 \times 50\ \mu A \\
&= 5\ mA
\end{aligned}
$$

As long as the collector-base junction remains reverse-biased, IC remains at 5 mA. This is true regardless of the actual voltage between the collector and base. In Fig. 19a, VCC can be varied from a few tenths of a volt to several volts with out having any effect on the collector current, IC! This is true provided the collector base breakdown voltage rating of the transistor is not exceeded. If VBB is increased to provide a base current, IB, of 100 μA, then IC = 100 x 100 μA = 10 mA. Again, if VCC is varied from a few tenths of a volt to several volts, IC remains constant. In Fig. 19a, notice that VCE = VCB + VBE . When VCB is a few tenths of a volt above zero, the collector-base diode is reverse-biased and IC = IB x βdc. This means that IC is controlled solely by the base current, IB, and not by the collector supply voltage VCC .

Transistor Operating Regions

Saturation Region

Figure 19b shows the action of the transistor for several different base currents. As can be seen, when VCE is zero, IC is zero because the collector-base function is not reverse-biased when VCE = 0. Without a positive voltage at the collector, it cannot attract electrons from the base. When VCE increases from zero, however, IC increases linearly. The vertical portion of the curves near the origin is called the saturation region. When a transistor is saturated, the collector current, IC, is not controlled solely by the base current, IB.

Breakdown Region

When the collector-base voltage is too large, the collector-base diode breaks down, causing a large, undesired collector current to flow. This is the breakdown region. This area of operation should always be avoided in transistor circuits. This region is not shown in Fig. 19b because it is assumed that breakdown will not occur when the circuit is designed properly.

Transistor Operating Regions

Cutoff Region

Notice the IB = 0 curve nearest the horizontal axis in Fig. 19b. This is called the cutoff region because only a small collector current, IC, flows. For silicon transistors, this current is very small and is therefore usually ignored. A transistor is said to be cut off when its collector current, IC, is zero.

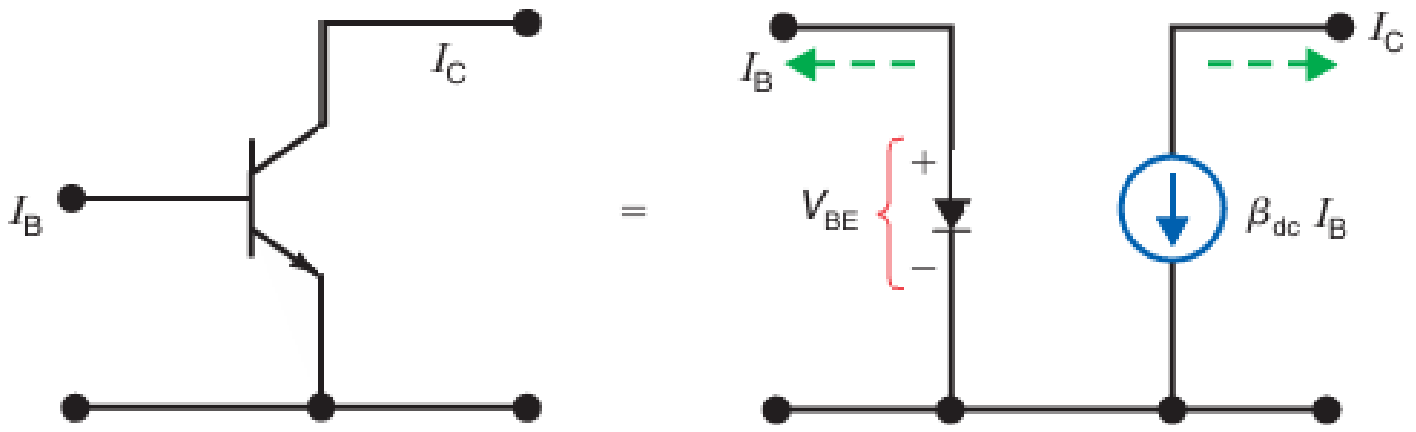
Active Region

The active region of a transistor is where the collector curves are nearly horizontal. When a transistor operates in the active region, the collector current, IC, is greater than the base current, IB, by a factor of beta or IC = βdc x IB . In the active region, the collector circuit acts like a current source.

Transistor Operating Regions

DC Equivalent of a Transistor

Figure 20 shows the dc equivalent circuit of a transistor operating in the active region. Notice that the base-emitter junction acts like a forward-biased diode with a current, IB. Usually, the second approximation of a diode is used, rather than the first or third. If the transistor is silicon, assume that VBE equals 0.7 V. Notice also that the collector circuit in Fig. 20 is replaced with a current source. The collector current source has an output current equal to βdc x IB. Ideally, the current source has infinite internal impedance. With the CE connection in Fig. 20, we note that the collector current, IC, is controlled only by the base current, IB, assuming βdc is a fixed quantity. When IB changes, IC still equals βdc x IB. In Fig. 20, the arrow in the current source symbol points in the direction of conventional current flow. Of course, electron flow is in the opposite direction, indicated by the dashed arrows for IB and IC.



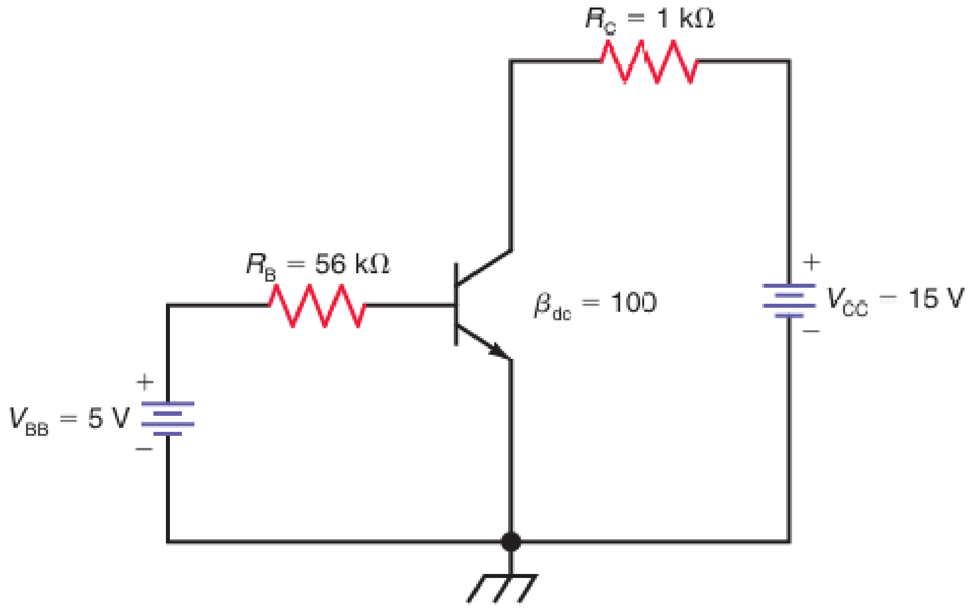
Transistor Biasing Techniques

For a transistor to function properly as an amplifier, an external dc supply voltage (or voltages) must be applied to produce the desired collector current, IC. Recall from our previous topic that the term bias is defined as a control voltage or current. Transistors must be biased correctly to produce the desired circuit voltages and currents. Several biasing techniques exist; the most common are discussed in this section. They include base bias, voltage divider bias, and emitter bias.

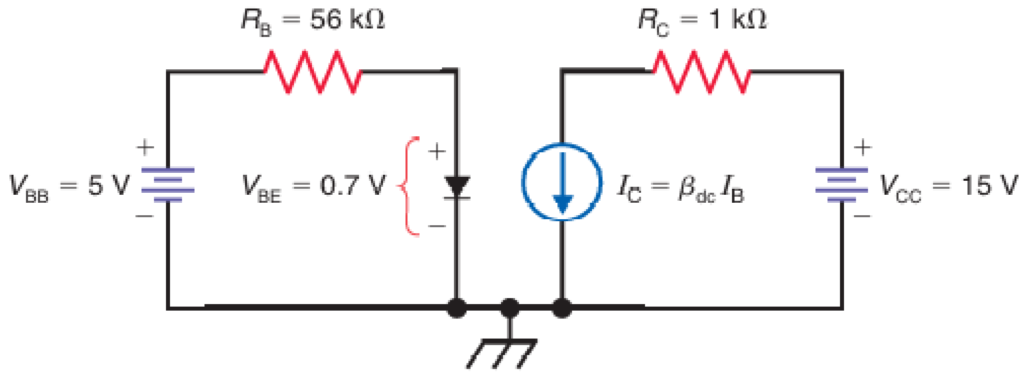
Transistor Biasing Techniques

Base Bias

Figure 21a shows the simplest way to bias a transistor, called base bias. VBB is the base supply voltage, which is used to forward-bias the base-emitter junction. RB is used to provide the desired value of base current, IB. VCC is the collector supply voltage, which provides the reverse-bias voltage required for the collector-base junction of the transistor. The collector resistor, RC, provides the desired voltage in the collector circuit. Figure 21b shows the dc equivalent circuit. For silicon transistors, VBE equals 0.7 V.



(a)

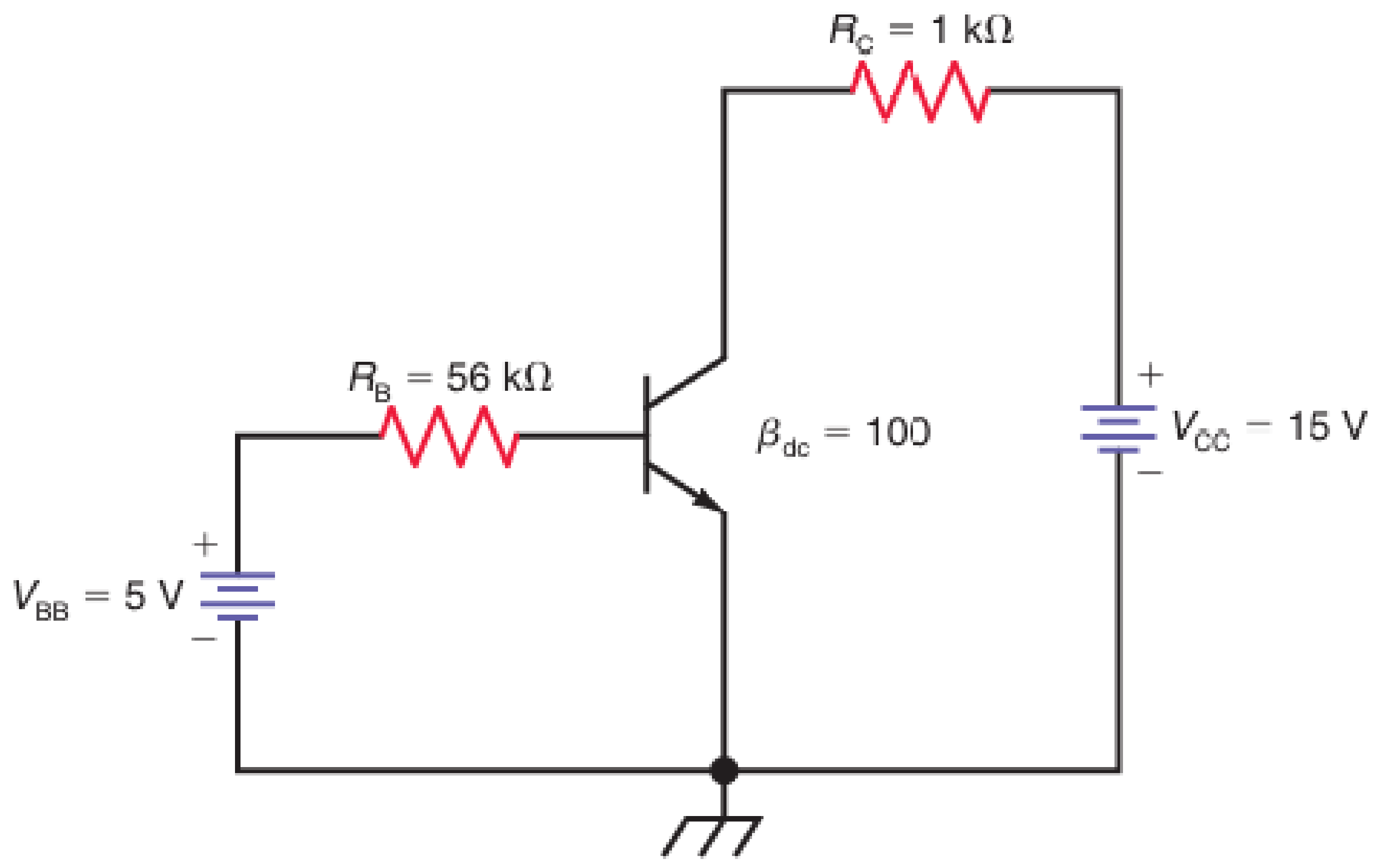


(b)

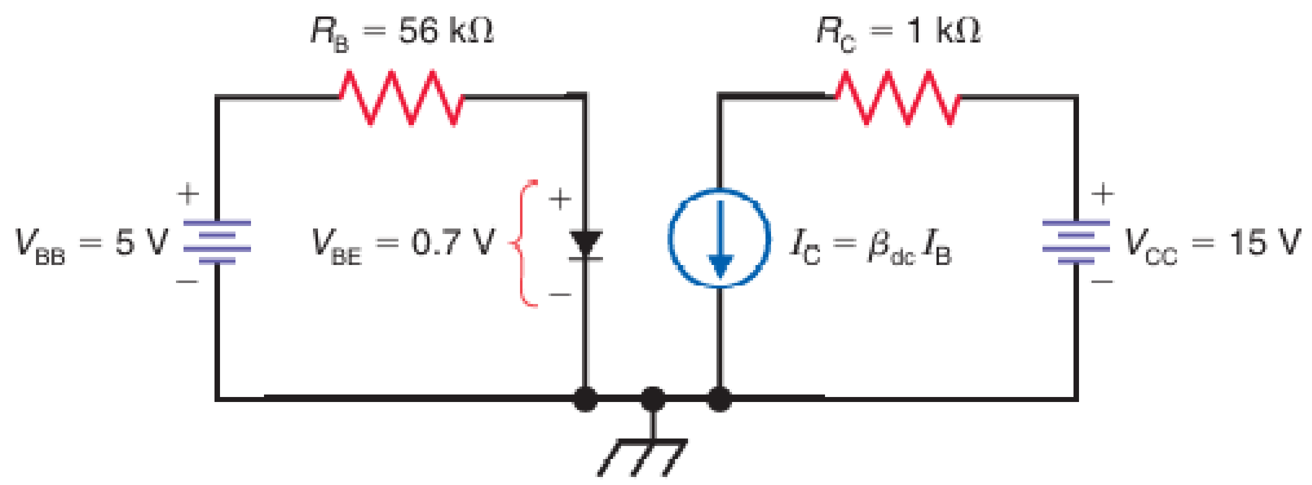
Transistor Biasing Techniques

Sample Problem

In the Figure shown below, solve for IB, IC, and VCE.



(a)

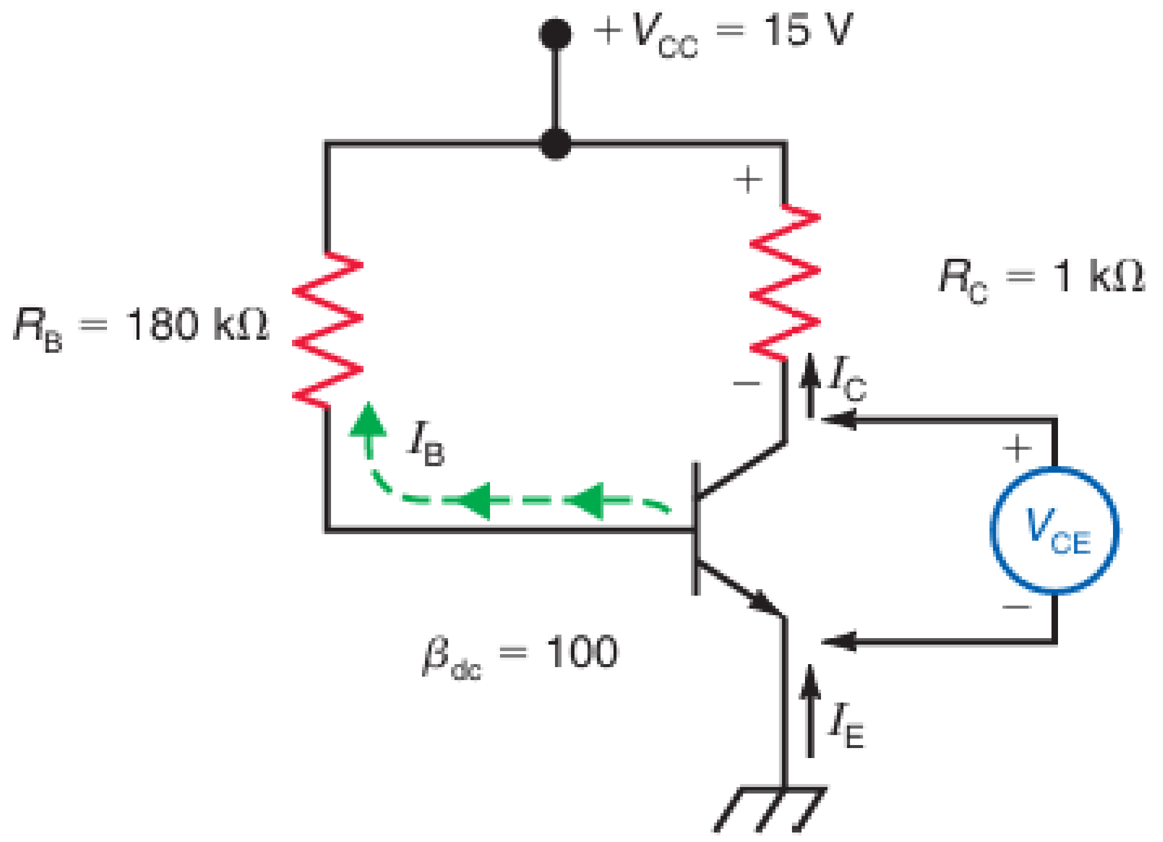


(b)

Transistor Biasing Techniques

Base Bias with Single Supply

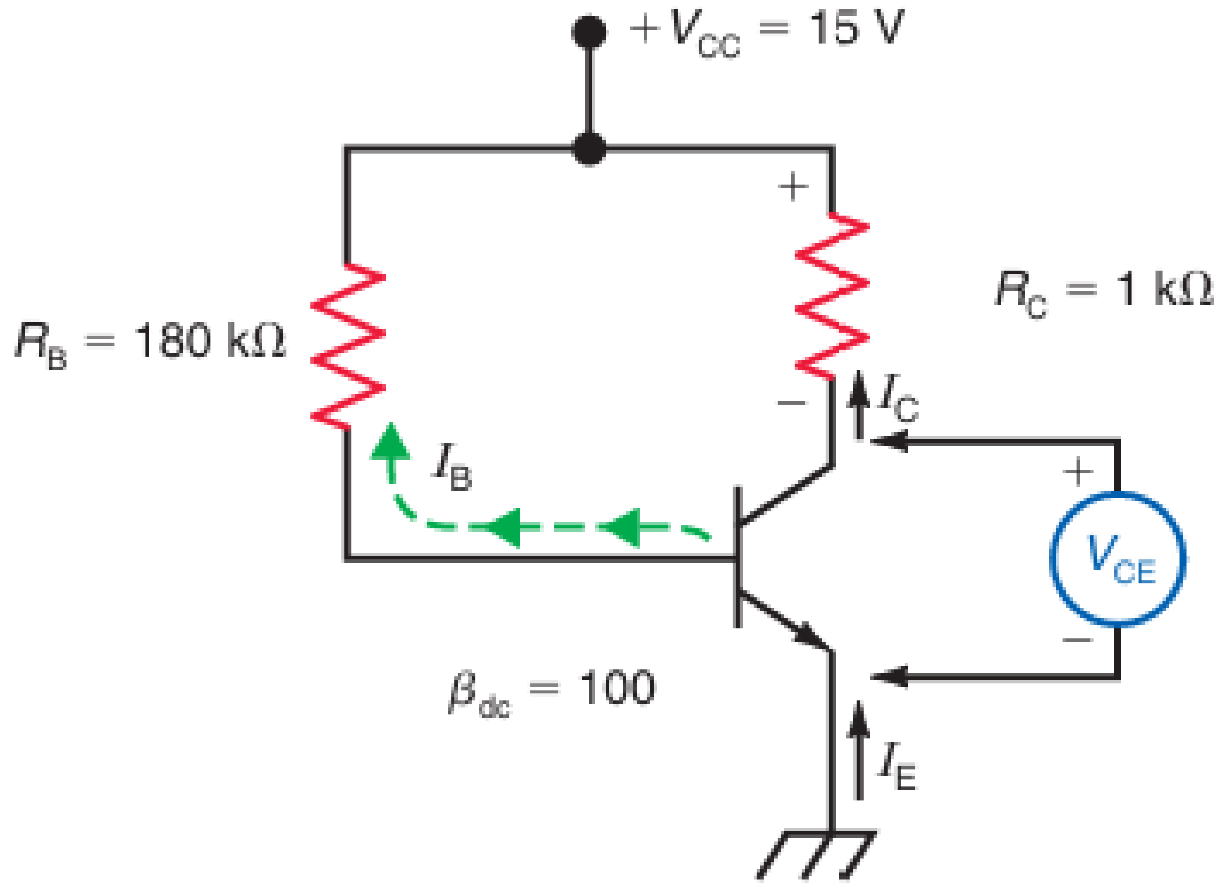
In most cases, a single voltage source provides the base bias for a transistor. One example is shown in Fig. 22. Notice that the base supply voltage, VBB, has been omitted and RB is connected to the positive (+) terminal of VCC.



Transistor Biasing Techniques

Sample Problems

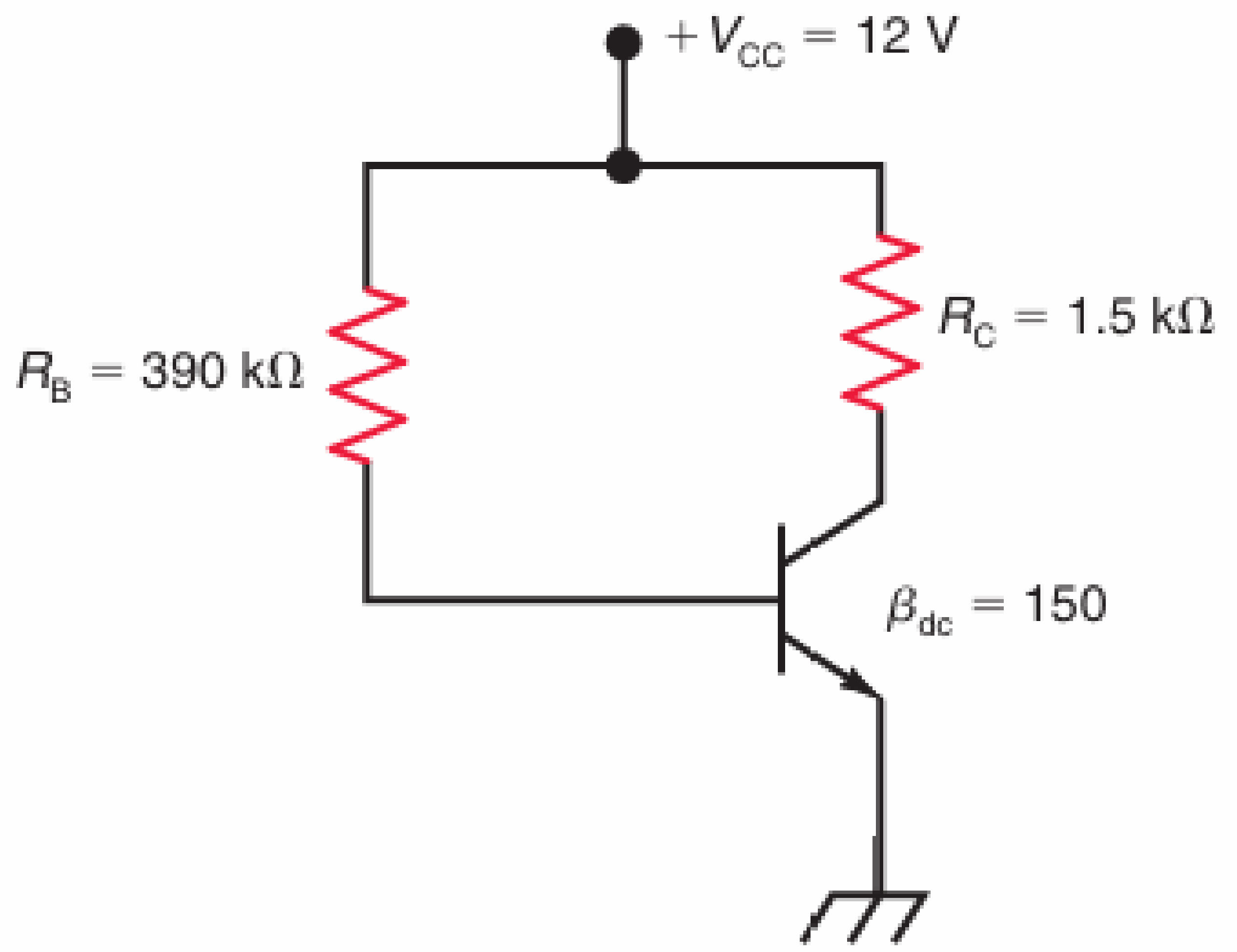
In Figure shown below, solve for IB, IC, and VCE.



Transistor Biasing Techniques

Sample Problems

In Figure shown below, solve for IB, IC, and VCE.

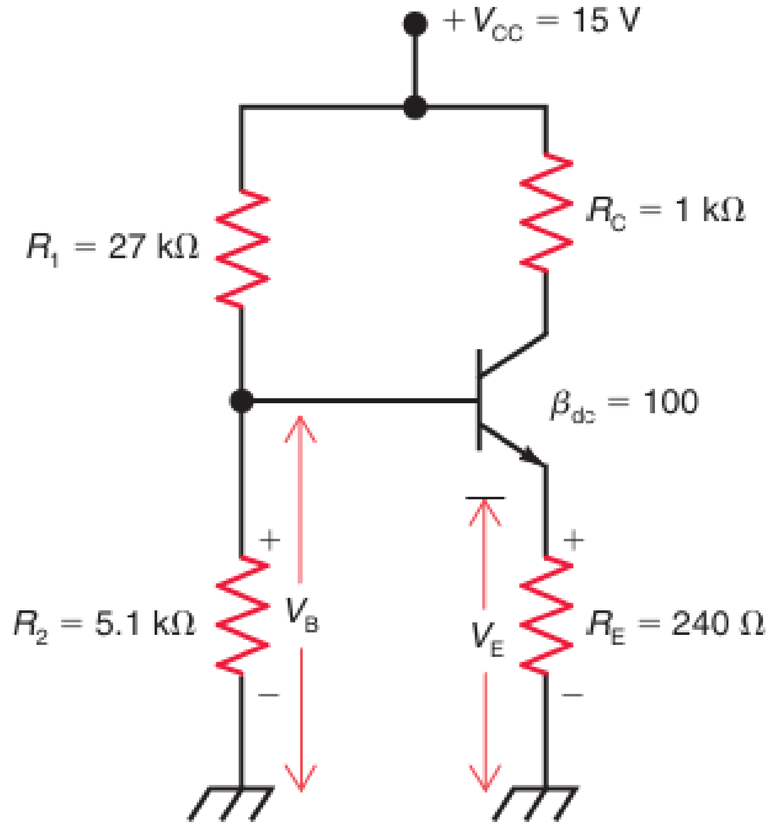


Transistor Biasing Techniques

Voltage Divider Bias

The most popular way to bias a transistor is with voltage divider bias. The advantage lies in its stability. If designed properly, the circuit is practically immune to changes in βdc caused by either transistor replacement or temperature variation. An example of voltage divider bias is shown in Fig. 23. Notice that VB is the voltage measured from the base lead to ground, which is actually the voltage drop across R2. Since the voltage divider is made up of R1 and R2, VB can be calculated using the voltage divider formula shown in Formula (12):

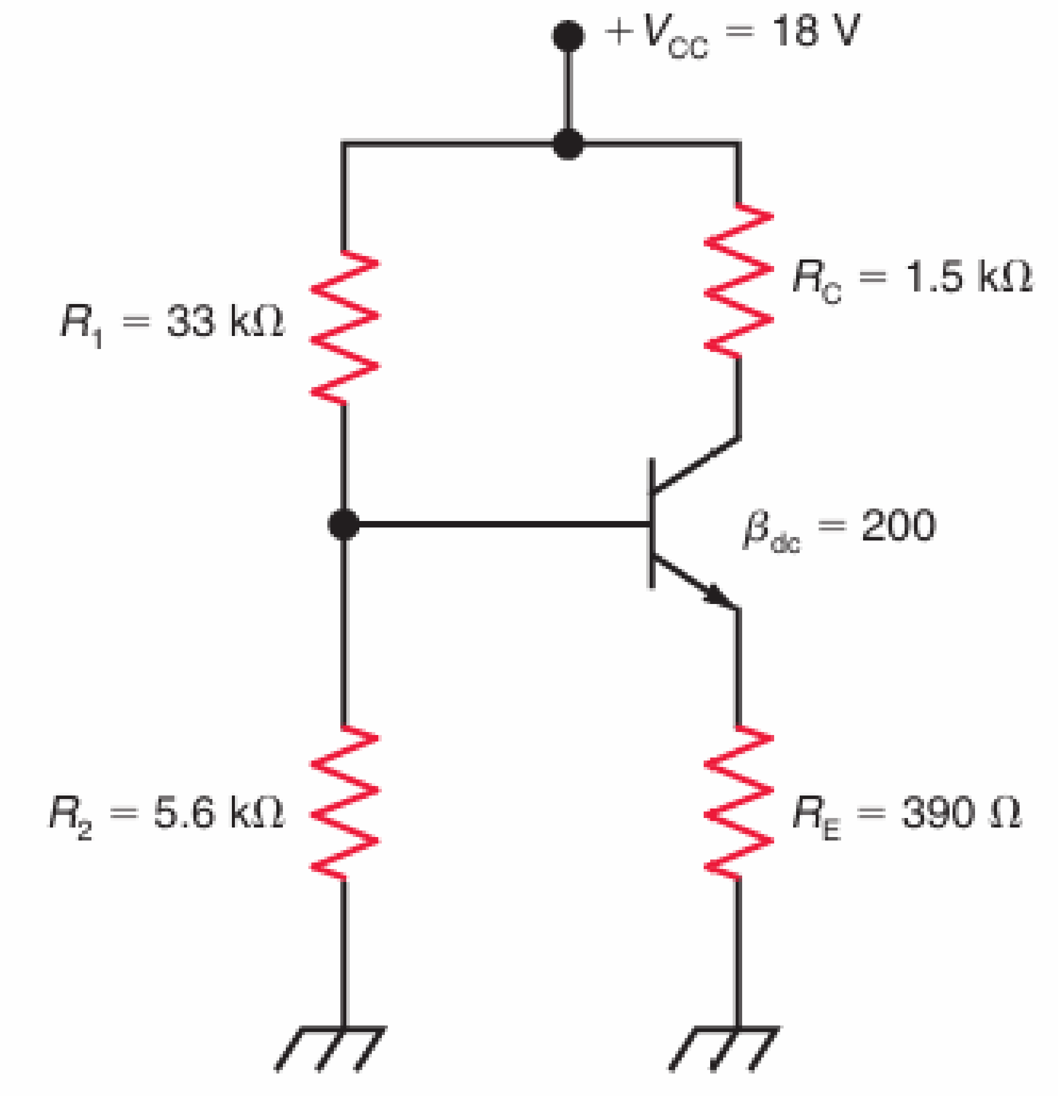
$$V_B = \frac{R_2}{R_1 + R_2} \times V_{CC}$$



Transistor Biasing Techniques

Sample Problem

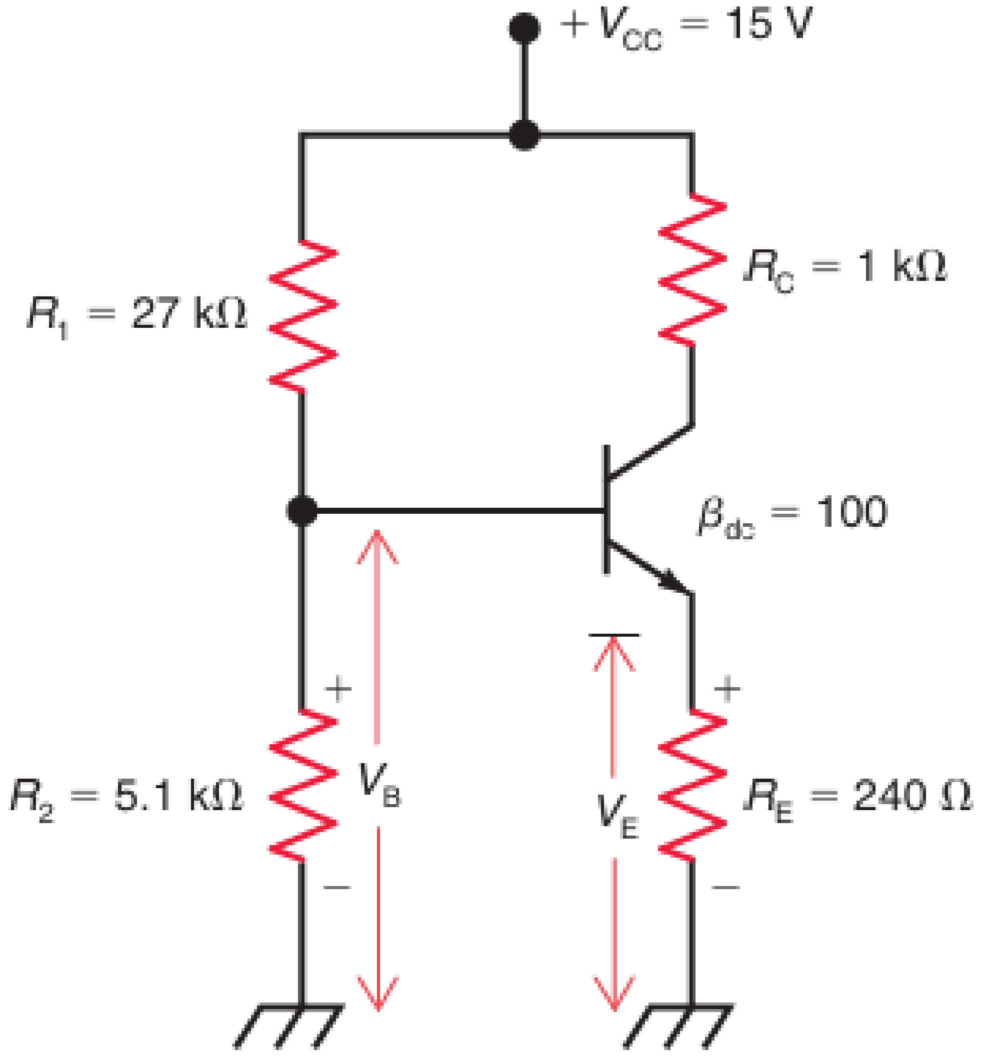
For the circuit shown in the Figure below, solve for VB, VE, IC, VC, and VCE.



Transistor Biasing Techniques

Sample Problem

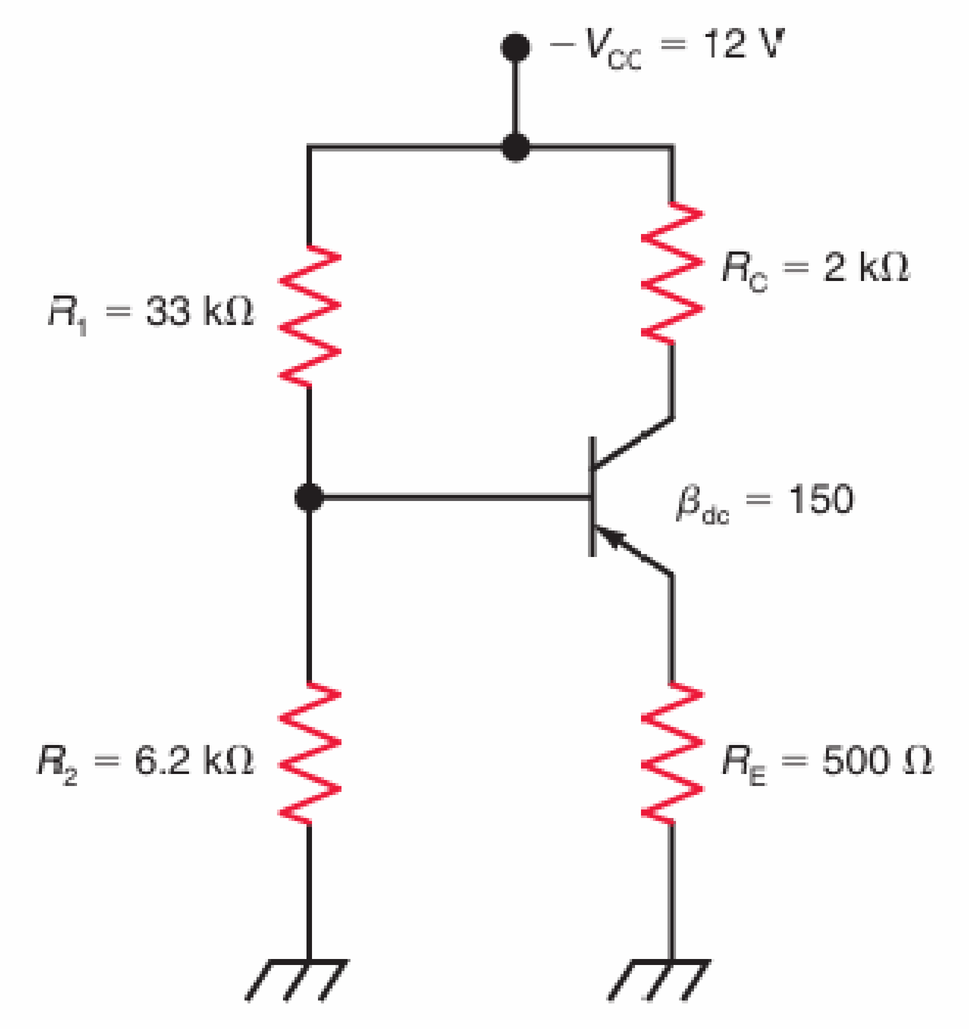
For the circuit shown in the Figure below, solve for VB, VE, IC, VC, and VCE.



Transistor Biasing Techniques

Sample Problem

For the pnp transistor in the Figure below, solve for VB, VE, IC, VC, and VCE.



Transistor Biasing Techniques

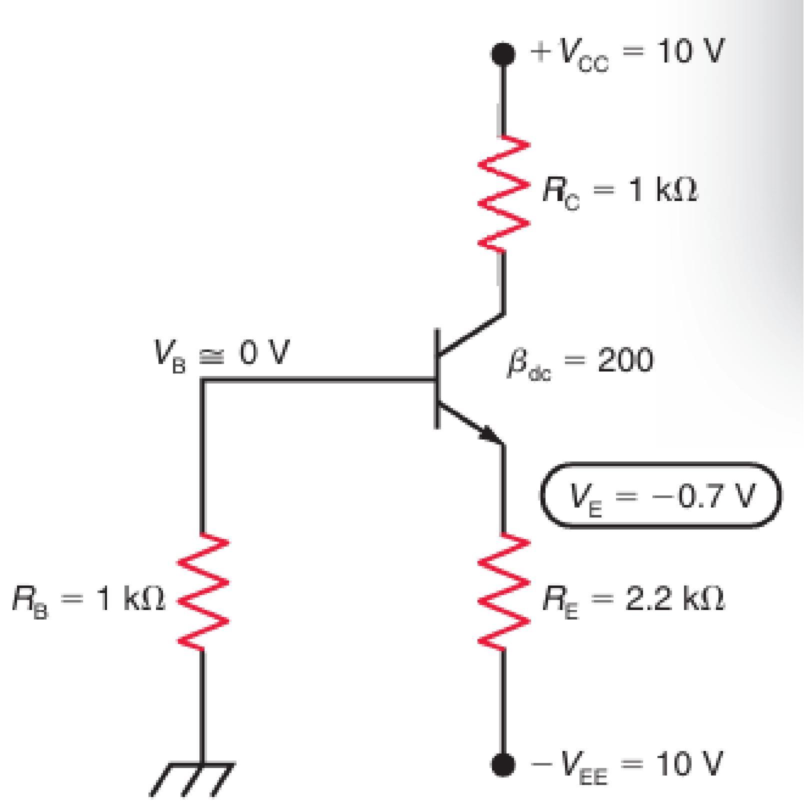
Emitter Bias

If both positive and negative power supplies are available, emitter bias provides a solid Q point that fluctuates very little with temperature variation and transistor replacement. An example of emitter bias is shown in Fig. 24. The emitter supply voltage, VEE, forward-biases the emitter-base junction through the emitter resistor, RE. To calculate the emitter current, IE, use Formula (13):

$$I_E = \frac{V_{EE} - V_{BE}}{R_E}$$

Notice that RB is ignored in the calculation for IE. A more exact formula for IE, however, is

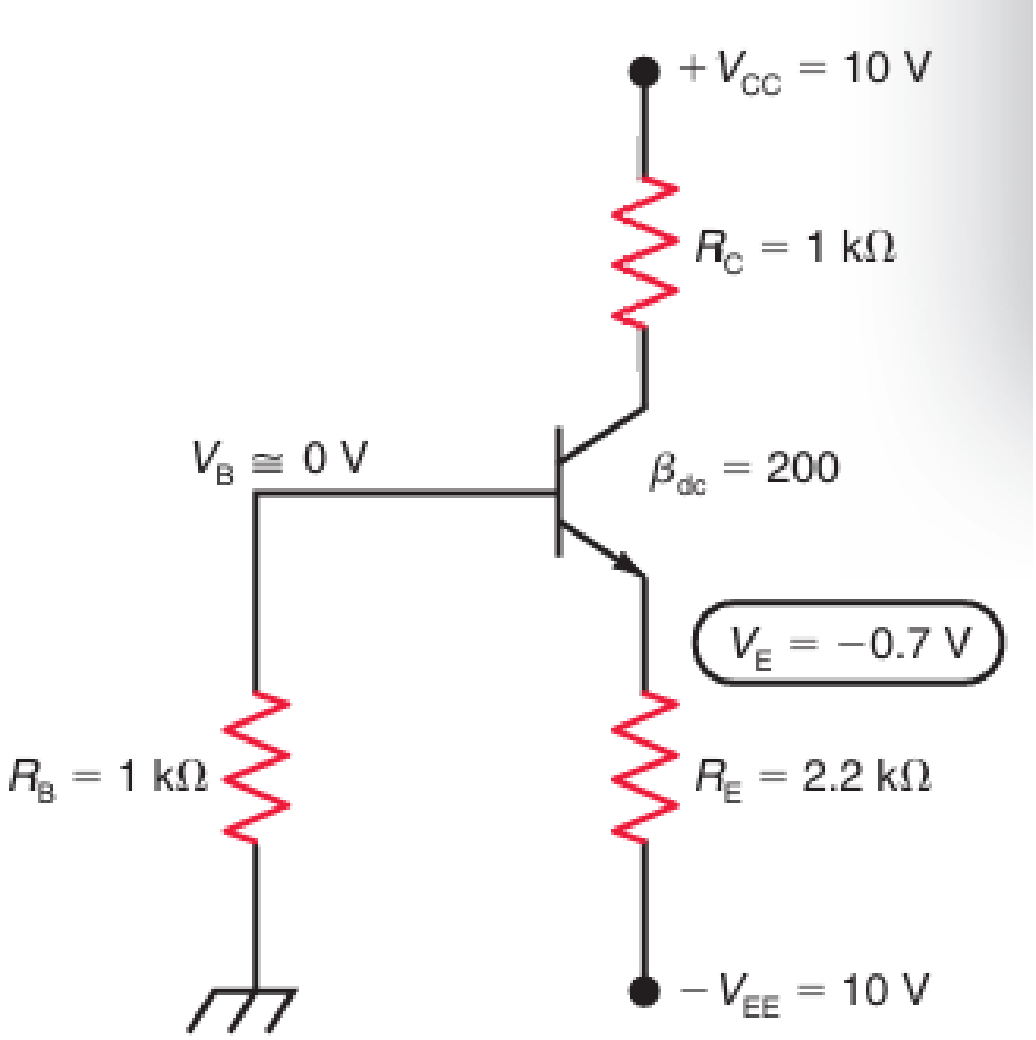
$$I_E = \frac{V_{EE} - V_{BE}}{R_E + \dfrac{R_B}{\beta_{dc}}}$$



Transistor Biasing Techniques

Sample Problems

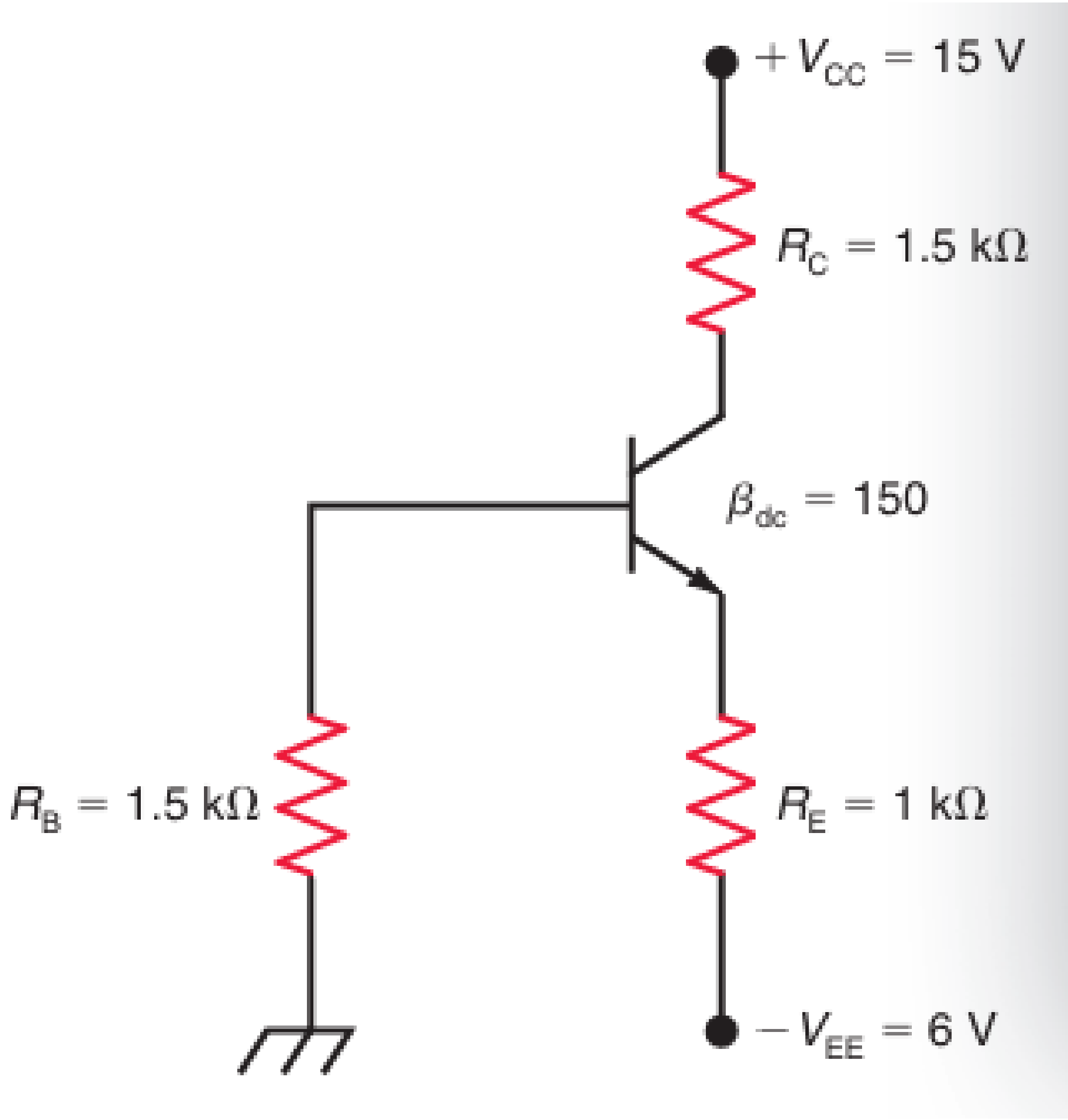
In the Figure shown below, calculate IE and VC.



Transistor Biasing Techniques

Sample Problems

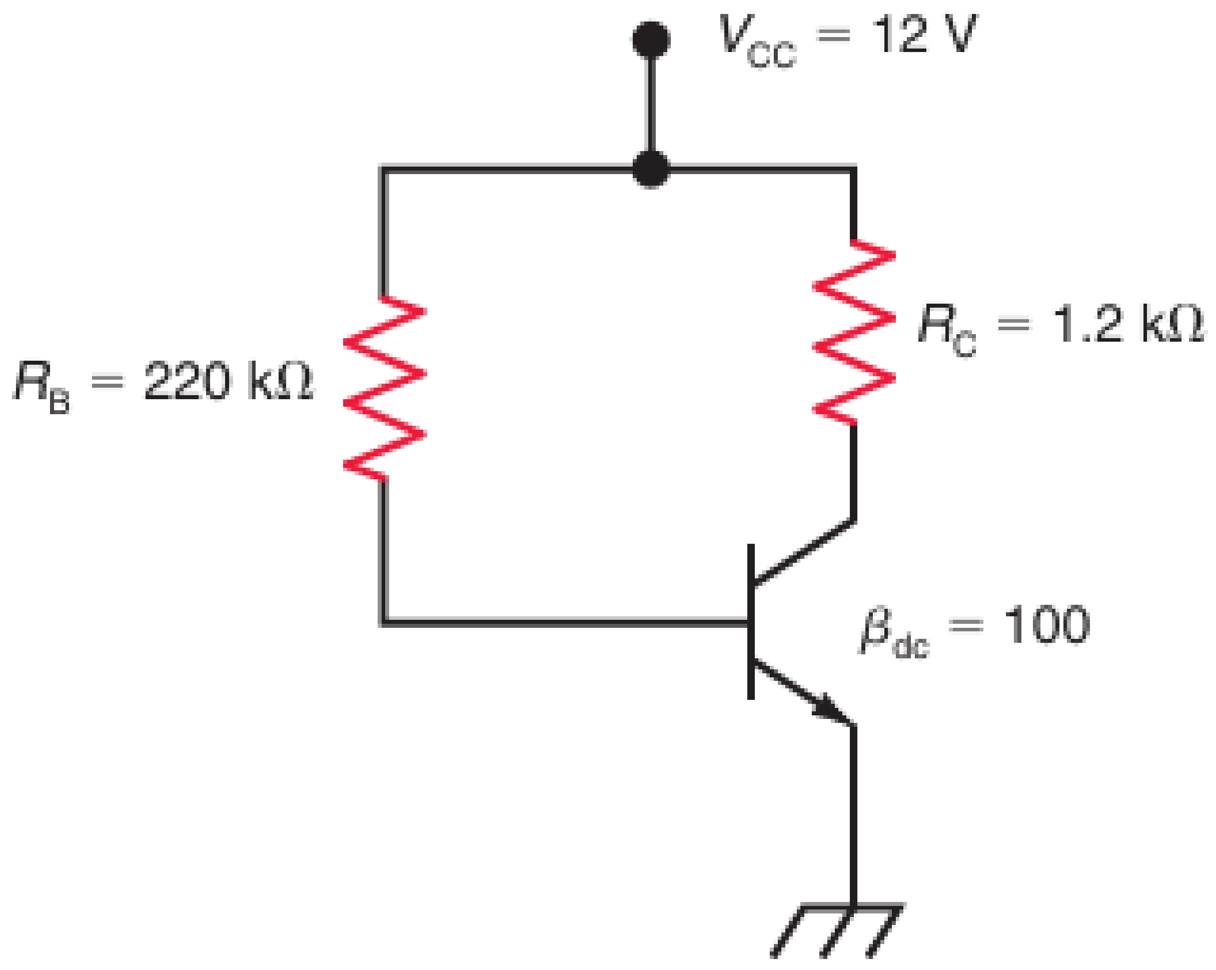
In the Figure shown below, calculate IE and VC.



Transistor Biasing Techniques

Try It Yourself!

In the Figure shown, solve for the following:
a. IB.
b. IC.
c. VCE.

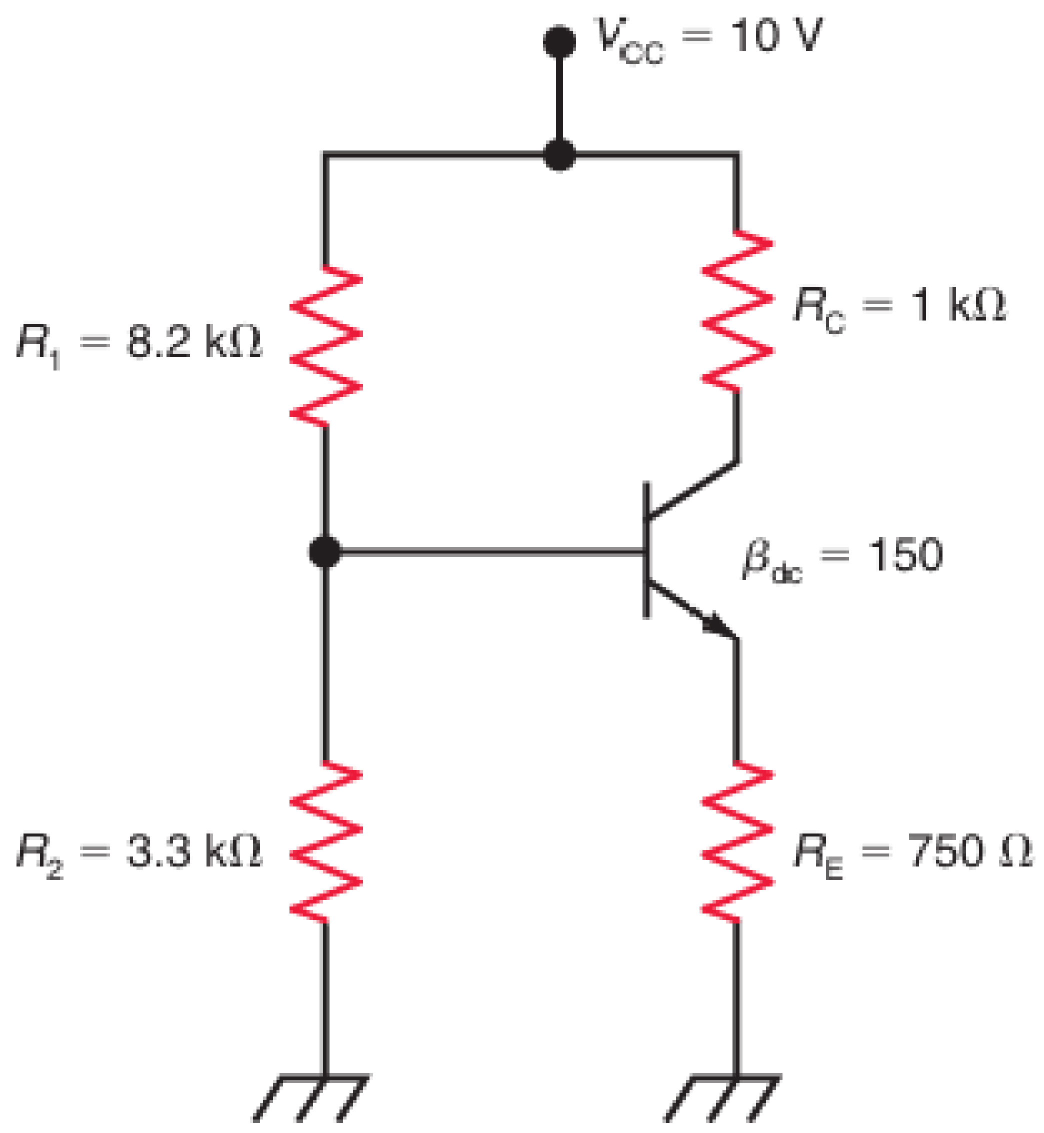


Transistor Biasing Techniques

Try It Yourself!

In the Figure shown, solve for the following:

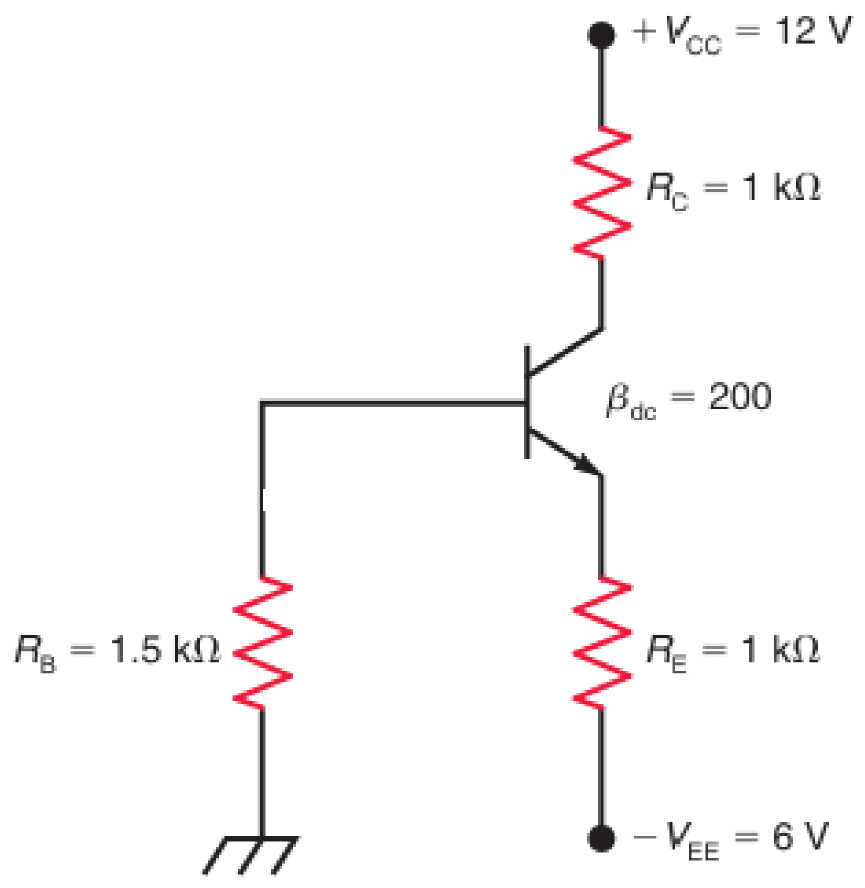
a. VB.
b. VE.
c. IC.
d. VC.
e. VCE.



Transistor Biasing Techniques

Try It Yourself!

In the Figure shown below, solve for IE and VC.



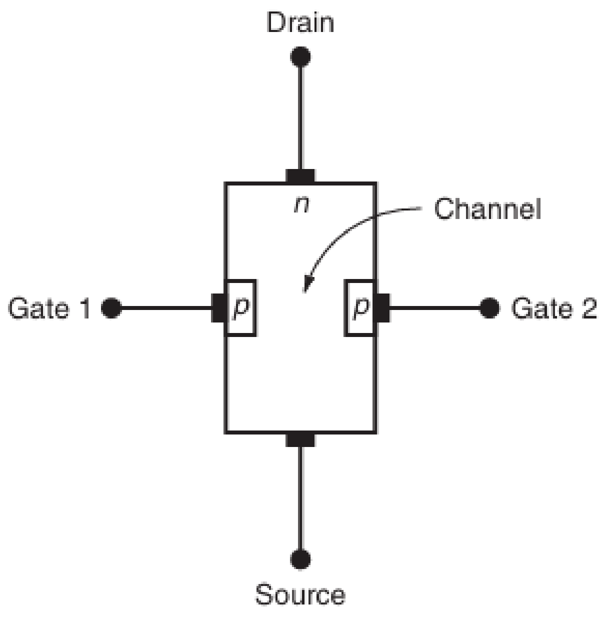
Field Effect Transistors

The field effect transistor (FET) is a three-terminal device similar to the bipolar junction transistor. The FET, however, is a unipolar device that depends on only one type of charge carrier, either free electrons or holes. There are basically two types of FETs: the junction field effect transistor, abbreviated JFET, and the metal-oxide-semiconductor field effect transistor, abbreviated MOSFET.

Unlike bipolar transistors, which are current-controlled devices, FETs are voltage-controlled devices, i.e., an input voltage controls an output current. The input impedance is extremely high (of the order of mega-ohms) for FETs and therefore they require very little power from the driving source. Their high input impedance is one reason that FETs are sometimes preferred over bipolar transistors.

JFETs and Their Characteristics

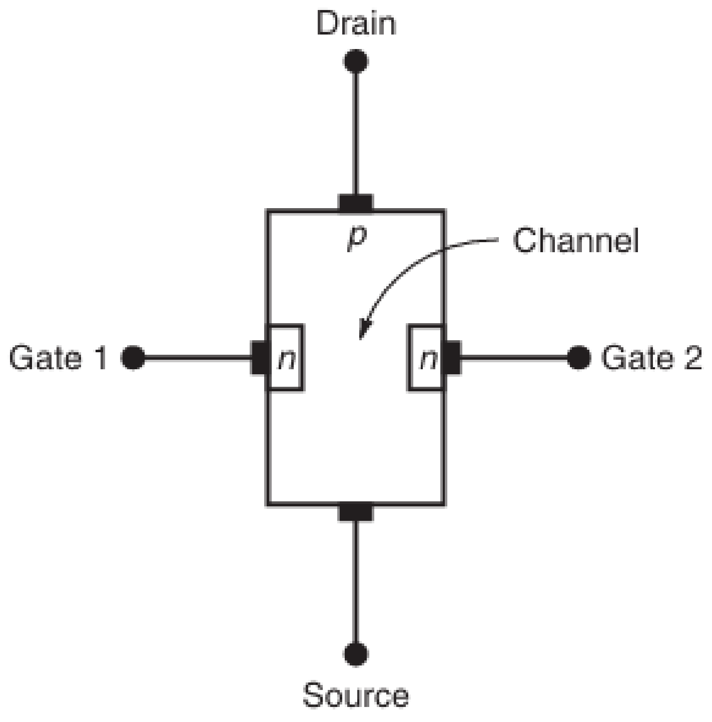
Figure 25a shows the construction of an n -channel JFET. Notice there are four leads: the drain, source, and two gates. The area between the source and drain terminals is called the channel. Because n-type semiconductor material is used for the channel, the device is called an n-channel JFET. Embedded on each side of the n-channel are two smaller p-type regions. Each p region is called a gate. When the manufacturer connects a separate lead to each gate, the device is called a dual-gate JFET. Dual-gate JFETs are most commonly used in frequency mixers, circuits that are frequently encountered in communications electronics. In most cases, the gates are internally connected and the device acts like a single-gate JFET.



(a)

JFETs and Their Characteristics

A p-channel JFET is shown in Fig. 25b . Embedded on both sides of the p-channel are two n-type gate regions. Again, these are normally connected together to form a single gate lead. The current flow is between the drain and source terminals in a JFET. For the n-channel JFET in Fig. 25a, the majority current carriers in the channel are free electrons. Conversely, for the p-channel JFET in Fig. 25b , the majority current carriers in the channel are holes.

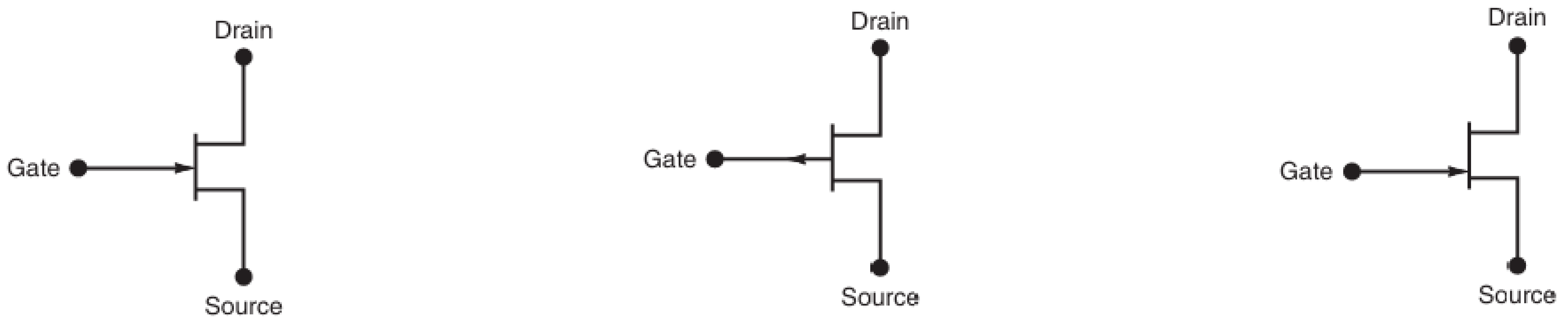


(b)

JFETs and Their Characteristics

Schematic Symbols

The schematic symbols for a JFET are shown in Fig. 26. Figure 26a is the schematic symbol for the n -channel JFET, and Fig. 26b shows the symbol for the p -channel JFET. Notice that the only difference is the direction of the arrow on the gate lead. In Fig. 26a, the arrow points in toward the n -type channel, whereas in Fig. 26b the arrow points outward from the p -type channel. In each symbol, the thin vertical line connecting the drain and source is a reminder that these terminals are connected to each end of the channel.



(a) (b) (c)

JFETs and Their Characteristics

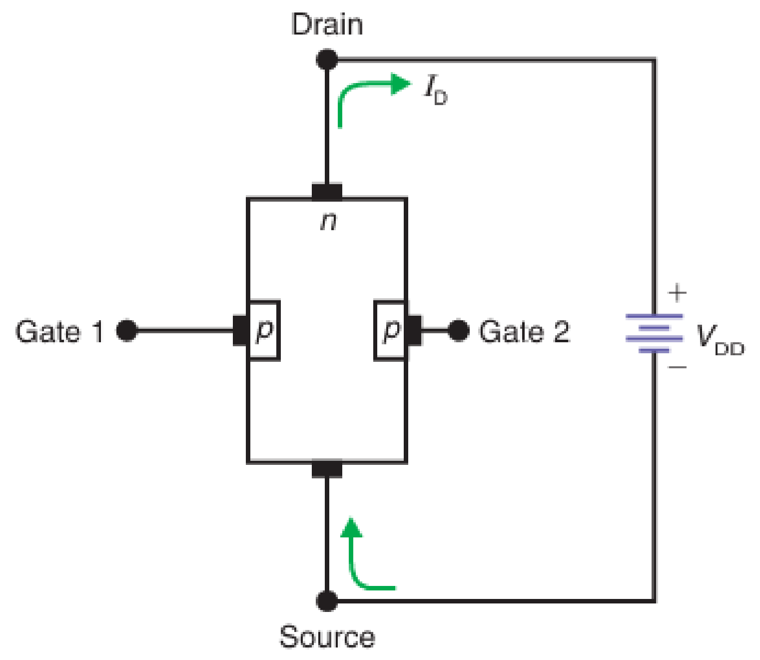
Schematic Symbols

One more point: When the gate regions of a JFET are located in the center of the channel, the JFET is said to be symmetrical, meaning that the drain and source leads may be interchanged without affecting its operation. If the construction of a JFET is such that the gate regions are offset from center, the JFET is called asymmetrical. The drain and source leads may not be interchanged in an asymmetrical JFET. Figure 26c represents the schematic symbol of an asymmetrical JFET, and Fig. 26a and b show the schematic symbols of a symmetrical JFET. Note that when the gates are offset from center in an asymmetrical JFET, they are placed close to the source terminal. This is shown in the schematic symbol of Fig. 26c .

JFETs and Their Characteristics

JFET Operation

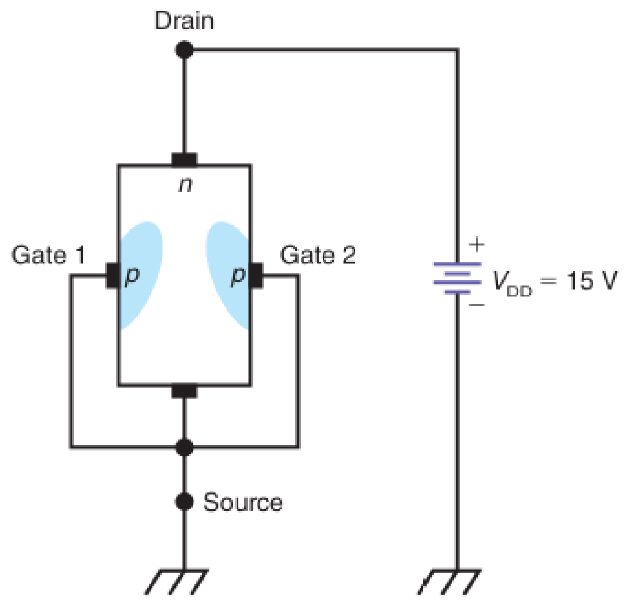
Figure 27 illustrates the current flow in an n -channel JFET with the p -type gates left disconnected. Here the amount of current flow depends upon two factors: the value of the drain-source voltage, VDS, and the drain-source resistance, designated rDS. Furthermore, the ohmic value of rDS is dependent on the doping level, cross-sectional area, and length of the doped semiconductor material used for the channel. In Fig. 27 electrons flow in the channel between the two p -type gate regions. Because the drain is made positive relative to the source, electrons flow through the channel from source to drain. In a JFET, the source current, IS, and the drain current, ID, are the same. In most cases, therefore, the current flow in the channel of a JFET is considered to be only the drain current, ID.



JFETs and Their Characteristics

Gate Action

The gate regions in a JFET are embedded on each side of the channel to help control the amount of current flow. Figure 28a shows an n -channel JFET with both gates shorted to the source. The drain supply voltage, VDD, reverse-biases both p-n junctions. This results in zero gate current. If both gates are centered vertically in the channel (which is the case for a symmetrical JFET), the voltage distribution over the length of the channel makes the width of the depletion layer wider near the top of the channel and narrower at the bottom. Thus, the depletion layers are shown to be wedge-shaped in Fig. 28a . Current flows in the channel between the depletion layers and not in the depletion layers themselves. The depletion layers penetrate deeply into the n -channel and only slightly into the p -type gate regions due to the different doping levels in the p and n materials.

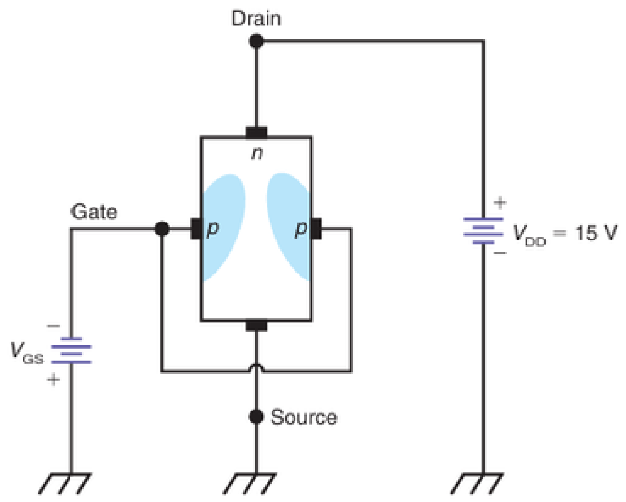


(a)

JFETs and Their Characteristics

Gate Action

Figure 28b shows how an n -channel JFET is normally biased. Not only is the drain made positive relative to the source, but the gate is made negative relative to the source. The effect of the negative gate voltage is to expand the width of the depletion regions, which in turn narrows the channel. Because the channel is narrower, the drain current, ID, is reduced. By varying the gate source voltage, designated VGS, the drain current, ID, can be controlled. Notice how much narrower the channel is in Fig. 28b versus 28a. If VGS is made negative enough, the depletion layers touch, which pinches off the channel. The result is zero drain current. The amount of gate-source voltage required to reduce the drain current, ID, to zero is called the gate-source cutoff voltage, designated VGS(off). The polarity of the biasing voltages for a p -channel JFET is opposite from that of an n -channel JFET. For a p -channel JFET, the drain voltage is negative and the gate voltage is positive.

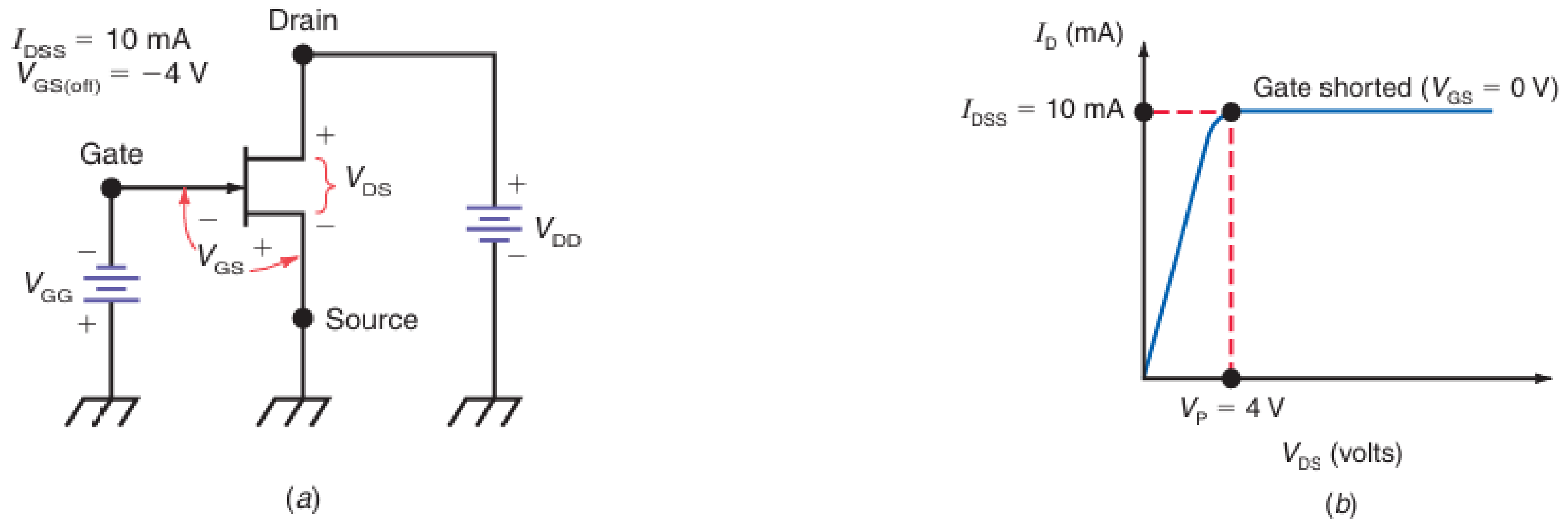


(b)

JFETs and Their Characteristics

Shorted Gate-Source Junction

Figure 29a shows an n -channel JFET connected to the proper biasing voltages. Note that the drain is positive and the gate is negative, creating the depletion layers depicted earlier in Fig. 28b. When the gate supply voltage, VGG, is reduced to zero in Fig. 29a, the gate is effectively shorted to the source and VGS equals zero volts. Figure 29b shows the graph of ID versus VDS (drain-source voltage) for this condition. As VDS is increased from zero, the drain current, ID, increases proportionally. When the drain-source voltage, VDS, reaches the pinch-off voltage, designated VP, the drain current, ID, levels off. In Fig. 29b, the pinch-off voltage, VP = 4 V. Technically, the pinch off voltage, VP, is the border between the ohmic region and current-source region. The region below VP is called the ohmic region because ID increases in direct proportion to VDS. Above VP is the current-source region, where ID is unaffected by changes in VDS.



JFETs and Their Characteristics

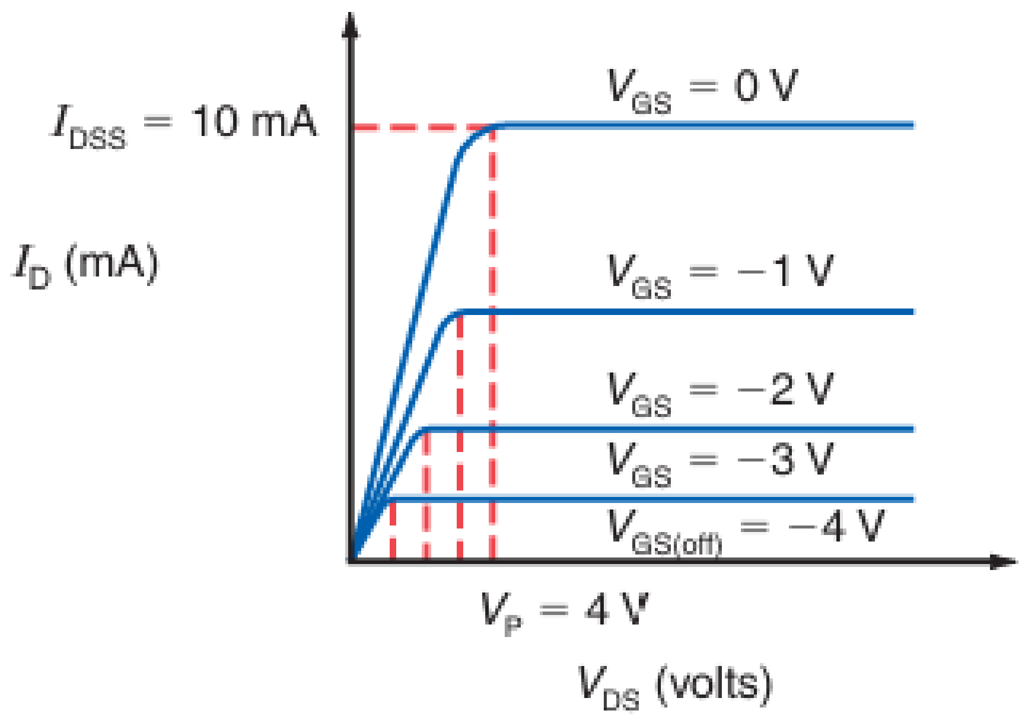
Shorted Gate-Source Junction

The drain current, ID, levels off above VP because at this point the channel resistance, rDS, increases in direct proportion to VDS. This results in a constant value of drain current for VDS values above the pinch-off voltage, VP. The maximum drain current that a JFET can have under normal operating conditions occurs when VGS is 0 V. This current is designated as IDSS. IDSS represents the drain-source current with the gate shorted. In Fig. 29b, IDSS 10 mA, a typical value for many JFETs. If VGS is negative, the drain current, ID, will be less than the value of IDSS; how much less depends on the value of VGS. It is important to note that JFETs are often referred to as “normally on ” devices because drain current flows when VGS is 0 V.

JFETs and Their Characteristics

Drain Curves

Figure 29c shows a complete set of drain curves for the JFET in Fig. 29a. Notice that as VGS becomes increasingly more negative, the drain current, ID, is reduced. Again, this is due to the fact that the channel is becoming much narrower with the increasing reverse bias in the gate regions.



(c)

JFETs and Their Characteristics

Drain Curves

Notice the magnitude of both VP and VGS(off) in Fig. 29c. It is interesting to note that for any JFET, VP=-VGS(off). Most data sheets do not list VP but almost always list VGS(off). The VGS(off) value of 4 V for the JFET in Fig. 29a is a typical value for many JFETs. In Fig. 29c, VP = -(-4 V) or VP = +4 V. There are two other important points to be brought out in Fig. 29c. The first is that the slope of each separate drain curve in the ohmic region decreases as VGS becomes more negative. This occurs because the channel resistance, rDS, increases as VGS becomes more negative. This useful feature allows using JFETs as voltage variable resistances. The second important feature is that the drain-source voltage, VDS, at which pinch-off occurs, decreases as VGS becomes more negative. Technically, the pinch-off value of VDS can be specified for any value of VGS. This is expressed in Formula (14):

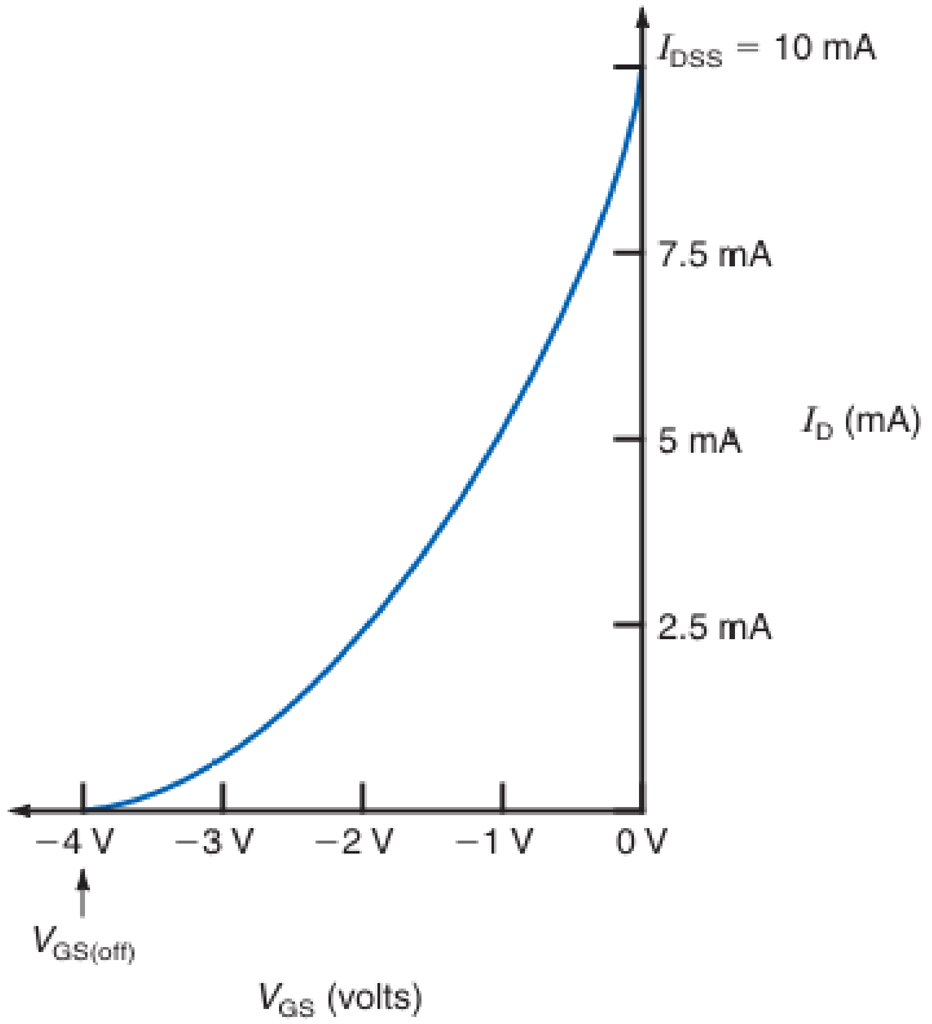
$$V_{\mathrm{DS(P)}} = V_{\mathrm{P}} - V_{\mathrm{GS}}$$

where VP is the pinch-off voltage for VGS = 0 V and VDS(P) is the pinch-off voltage for any value of VGS. In Formula (14), VDS(P), VP, and VGS are absolute values, that is, their polarities are ignored. For any value of VGS, VDS(P) is the border between the ohmic and current-source regions.

JFETs and Their Characteristics

Transconductance Curve

Figure 30 shows a graph of ID versus VGS for the JFET in Fig. 29. This curve is called a transconductance curve. Notice that the graph is not linear because equal changes in VGS do not produce equal changes in ID.



JFETs and Their Characteristics

Calculating the Drain Current

When the values of IDSS and VGS(off) are known for any JFET, the drain current, ID, can be calculated using Formula (15):

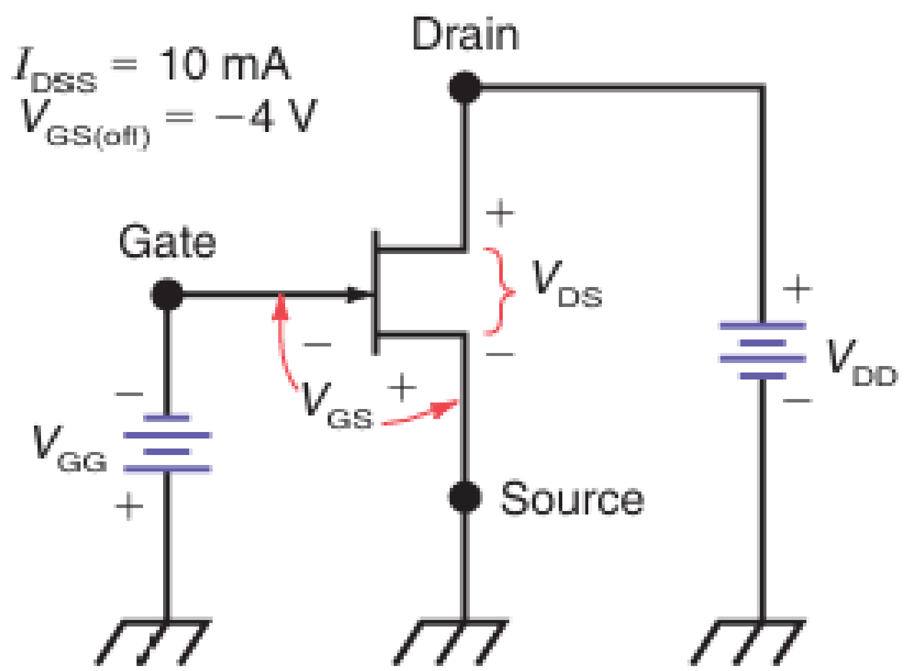
$$I_D = I_{DSS}\left[1 - \frac{V_{GS}}{V_{GS(off)}}\right]^2$$

Formula (15) holds true only when VDS is equal to or greater than VDS (P). Formula (15) can be used for any JFET (n -channel or p -channel) when IDSS and VGS (off) are known.

JFETs and Their Characteristics

Sample Problem

In Fig. 29a calculate the drain current, ID, for the following values of VGS : (a) 0 V, (b) 0.5 V, (c) 1 V, (d) 2 V, (e) 3 V. Assume VDS ≥ VDS(P) .



(a)

JFETs and Their Characteristics

More about the Ohmic Region

When V_{DS} is below $V_{DS(P)}$, Formula (15) no longer applies. Instead the JFET must be considered a resistance. This resistance is designated $r_{DS(on)}$. The exact value of $r_{DS(on)}$ for a given JFET is dependent on the value of V_{GS}. When $V_{GS} = 0$ V, $r_{DS(on)}$ has its lowest value. When $V_{GS} = V_{GS(off)}$, $r_{DS(on)}$ approaches infinity. The main point is that the channel resistance, $r_{DS(on)}$, increases as V_{GS} becomes more negative. As mentioned earlier, this useful feature allows using the JFET as a voltage-variable resistance.

The ohmic resistance of a JFET can be determined for any value of V_{GS} by using the following formula:

$$r_{DS} = \frac{R_{DS(on)}}{1 - \frac{V_{GS}}{V_{GS(off)}}}$$

where $R_{DS(on)}$ is the ohmic resistance when V_{DS} is small and $V_{GS} = 0$ V.

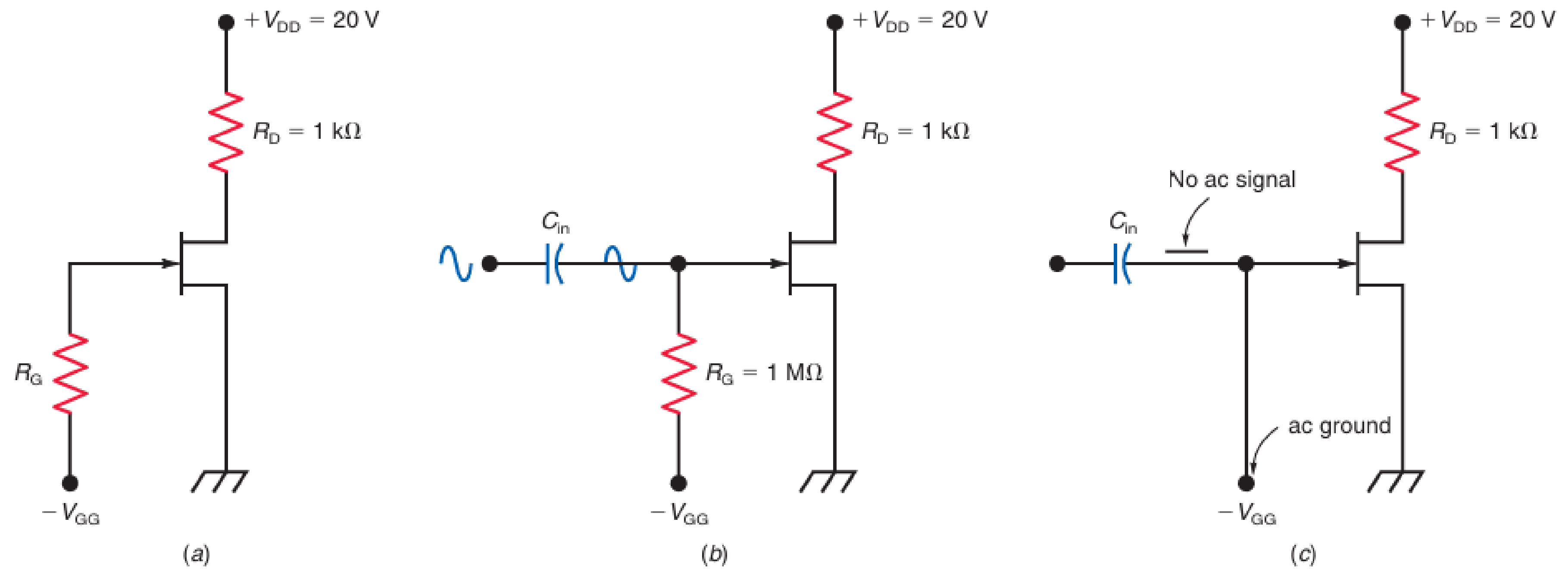
JFET Biasing Techniques

Many techniques can be used to bias JFETs. In all cases, however, the gate-source junction is reverse-biased. The most common biasing techniques are covered in this section including gate bias, self-bias, voltage divider bias, and current-source bias.

JFET Biasing Techniques

Gate Bias

Figure 31a shows an example of gate bias. The negative gate voltage is applied through a gate resistor, RG. RG can be any value, but it is usually 100 kΩ or larger. Since there is zero current in the gate lead of the JFET, the voltage drop across RG is zero. The main purpose of RG is to isolate the gate from ground for ac signals. Figure 31b shows how an ac signal is coupled to the gate of a JFET. If RG were omitted, as shown in Fig. 31c, no ac signal would appear at the gate because VGG is at ground for ac signals. RG is usually made equal to the value desired for the input impedance, Zin, of the amplifier. Since the gate-source junction of the JFET is reverse-biased, its impedance is at least several hundred megohms, and therefore Zin = RG. In Fig. 31b, RG = 1 MΩ, so Zin = 1 MΩ also.



JFET Biasing Techniques

Gate Bias

When VGS is known, the value of the drain current is calculated using Formula (16). Then VDS is calculated as

$$V_{DS} = V_{DD} - I_D R_D$$

Gate bias is seldom used with JFETs because the characteristics of the individual JFETs used in mass production may vary over a wide range. Thus, for some circuits, the amount of VGS applied to the JFET may provide a very large drain current, whereas in other circuits, the same gate voltage might reduce the drain current, ID, to nearly zero.

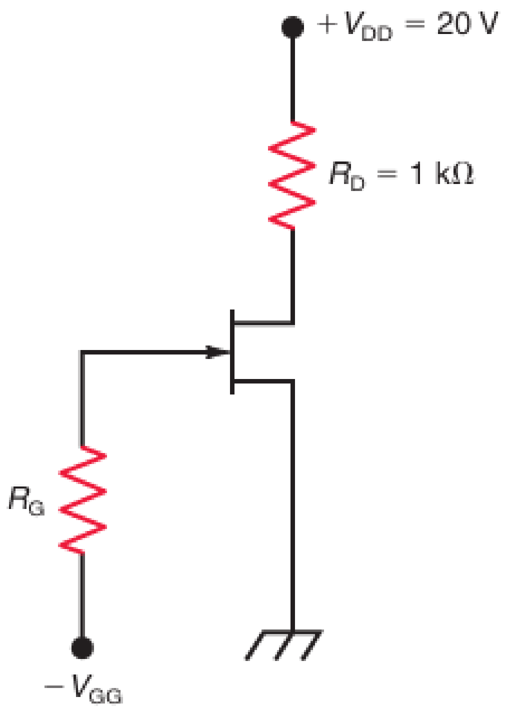
JFET Biasing Techniques

Sample Problems

Assume that the JFET circuit in Fig. 31a is to be mass-produced. The JFET has the following parameters:

Parameter	Minimum	Maximum
I_{DSS}	2 mA	20 mA
$V_{GS(off)}$	-2 V	-8 V

For the range of JFET parameters shown, calculate the minimum and maximum values for ID and VDS if VGS = -1.5 V.



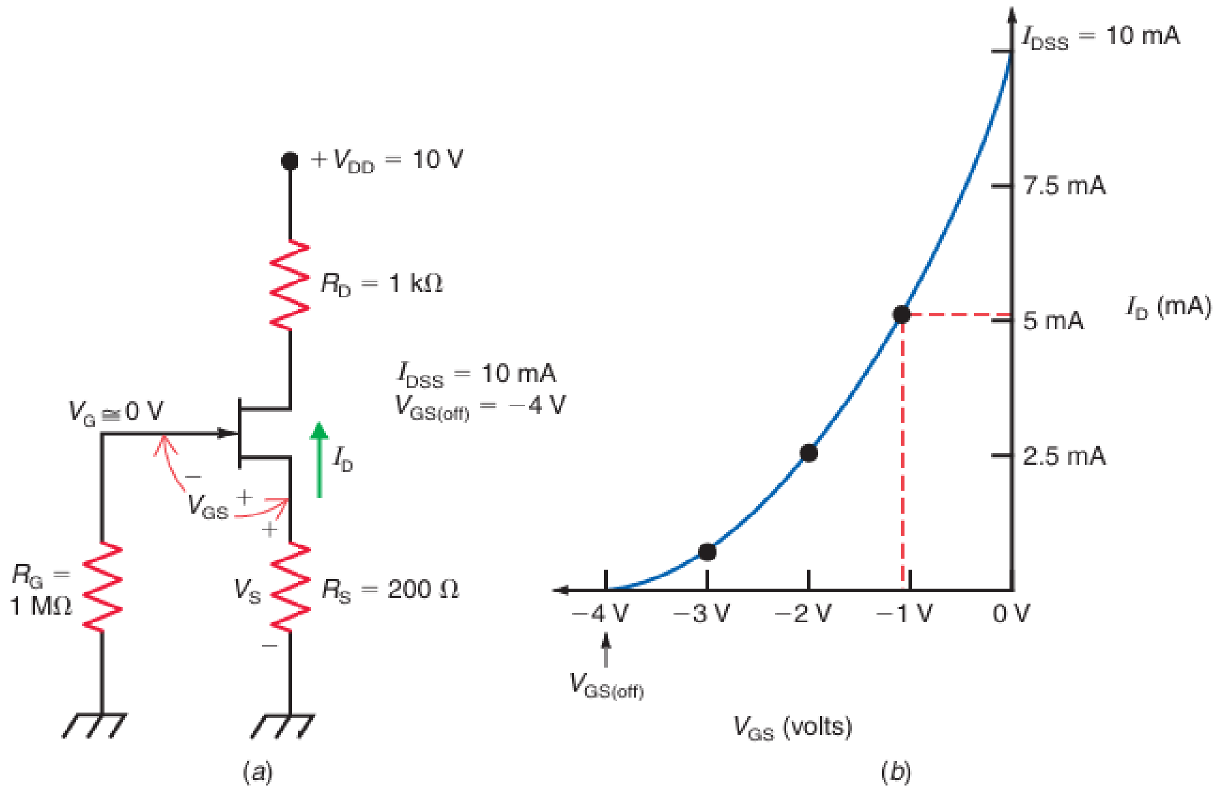
(a)

JFET Biasing Techniques

Self-Bias

One of the most common ways to bias a JFET is with self-bias. (See Fig. 32a.) Notice that only a single power supply is used, the drain supply voltage, VDD. In this case, the voltage across the source resistor, RS, provides the gate-to-source bias voltage. But how is this possible? Here's how. When power is first applied, drain current flows and produces a voltage drop across the source resistor, RS. For the direction of drain current shown, the source is positive with respect to ground. Because there is no gate current, VG = 0 V. Therefore VGS is calculated as

$$V_{GS} = V_G - V_S$$



JFET Biasing Techniques

Self-Bias Calculations

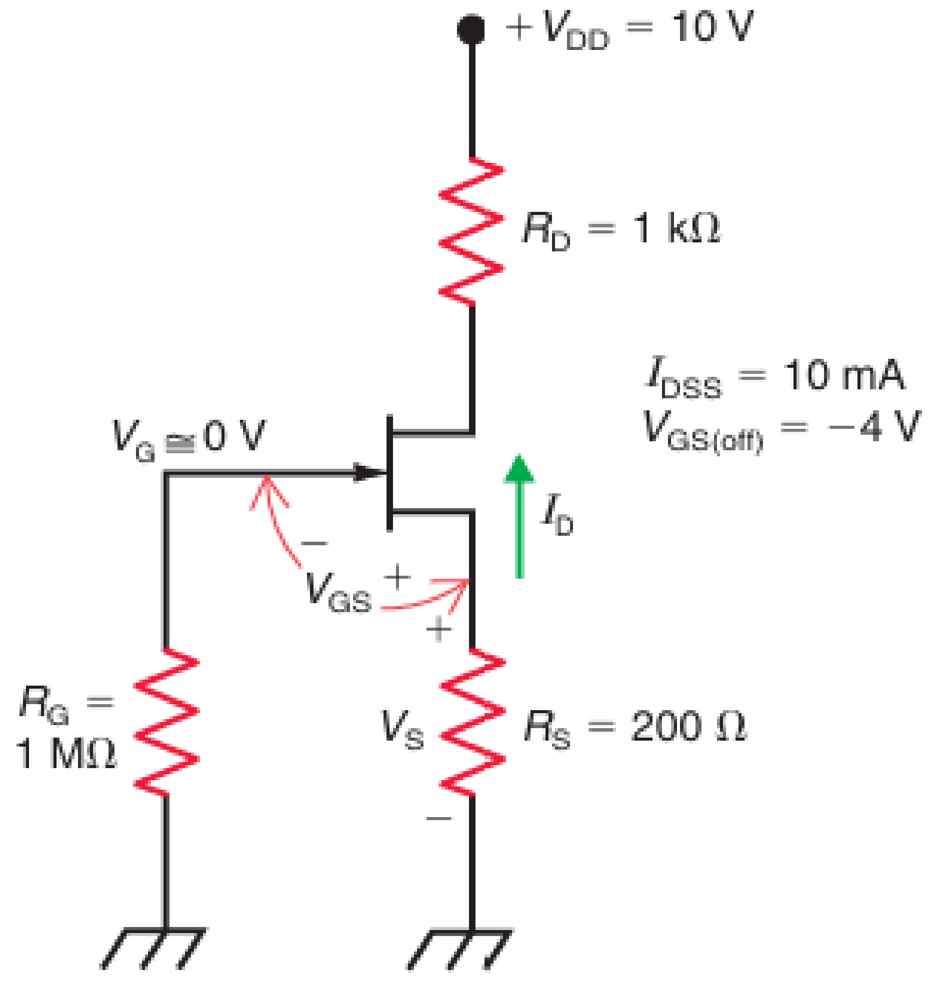
The source resistor, RS, must be carefully selected for any JFET circuit with self bias. Normally the source resistor, RS, is chosen so that the drain current, ID, equals approximately one-half of IDSS. To do this, VGS must be set equal to approximately one-fourth the value of VGS(off). This is a rough approximation that provides reasonably accurate results. [To prove that ID = IDSS/2 when VGS = VGS(off)/4 , rearrange Formula (15).] A convenient formula for determining the source resistor, RS, is

$$R_S = \frac{-V_{GS(off)}}{2I_{DSS}}$$

JFET Biasing Techniques

Sample Problem

In the Figure shown below calculate the drain voltage, VD.



(a)

JFET Biasing Techniques

Voltage Divider Bias

Figure 33 shows a JFET with voltage divider bias. Since the gate-source junction has extremely high resistance (several hundred megohms), the R1 - R2 voltage divider is practically unloaded. Therefore, the gate voltage, VG, is calculated as

$$V_G = \frac{R_2}{R_1 + R_2} \times V_{DD}$$

The source voltage, V_S, is calculated as

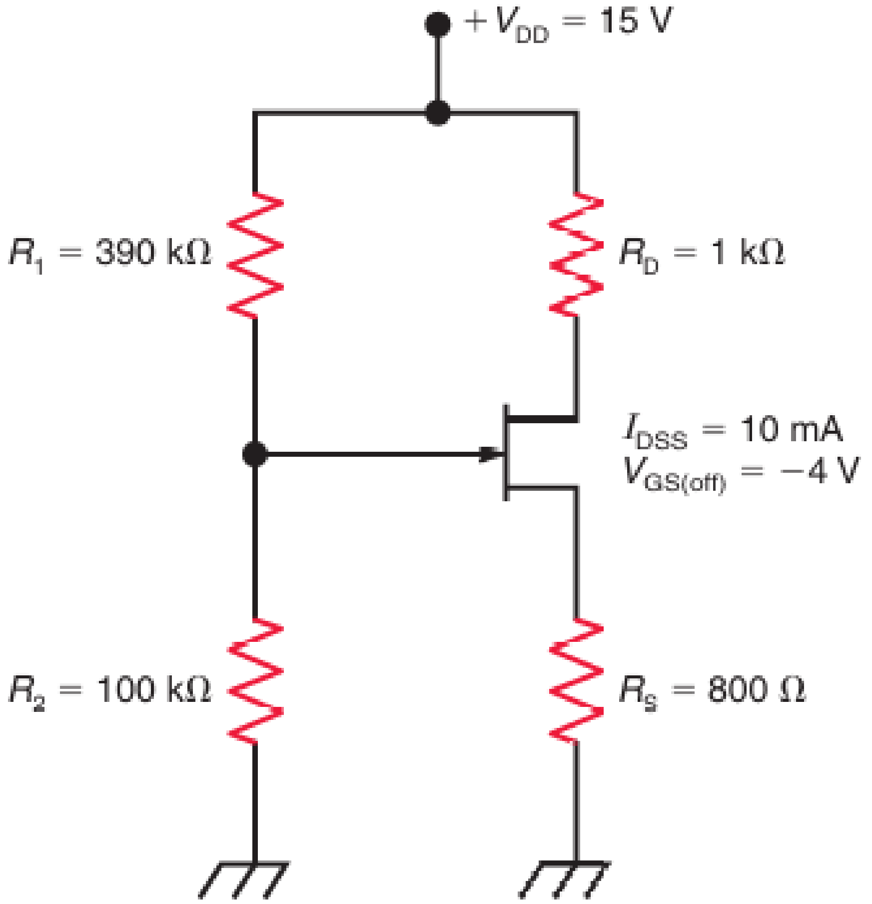
$$V_S = V_G - V_{GS}$$

Since $I_D = I_S$, the drain current is

$$I_D = \frac{V_S}{R_S}$$

Also, the drain voltage, V_D, is

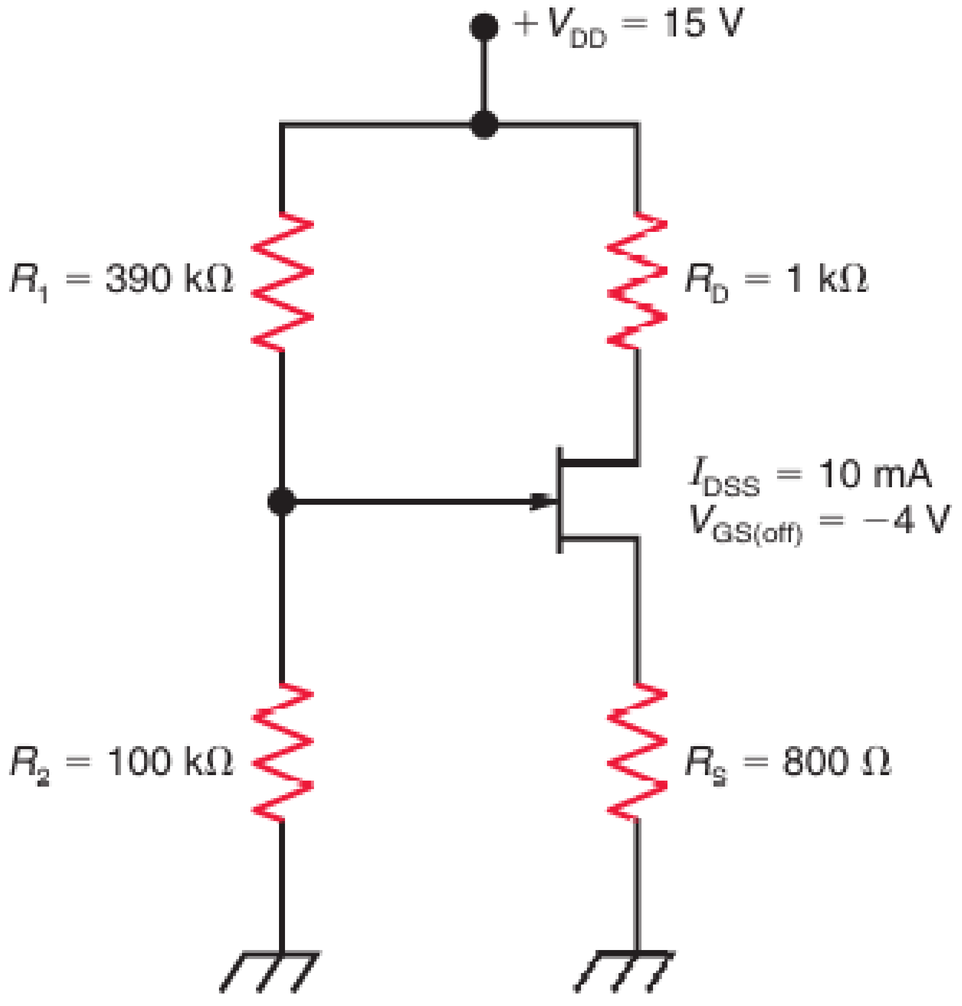
$$V_D = V_{DD} - I_D R_D$$



JFET Biasing Techniques

Sample Problem

In the Figure shown below, VGS = - 1 V. Calculate VG, VS, ID, and VD.



JFET Biasing Techniques

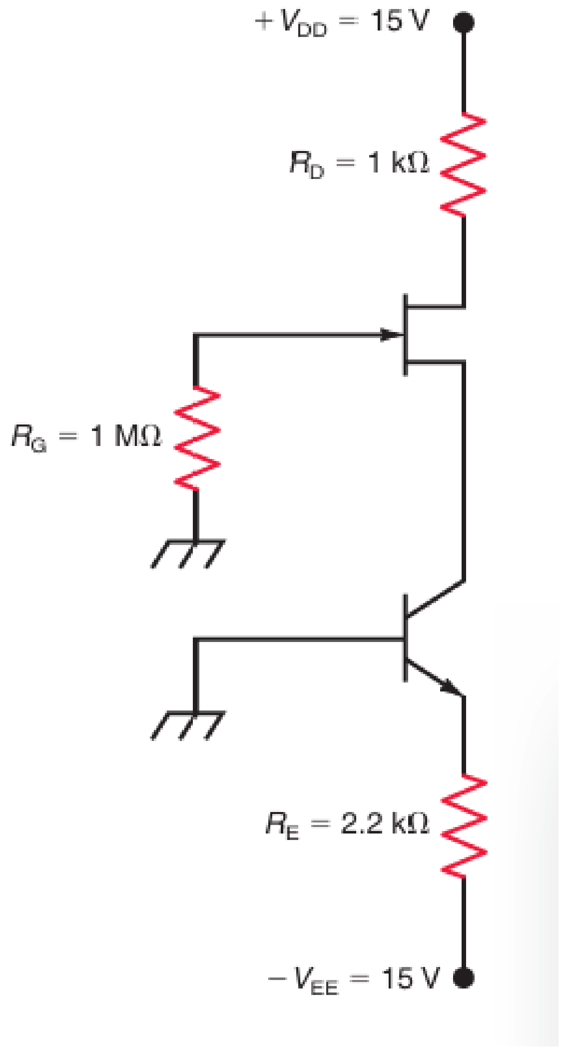
Current-Source Bias

Figure 34 shows one of the best ways to bias JFETs. The npn transistor with emitter bias acts like a current source for the JFET. The drain current, ID, equals the collector current, IC, which is independent of the value of VGS. Therefore,

$$I_C = I_D$$

I_C is calculated as

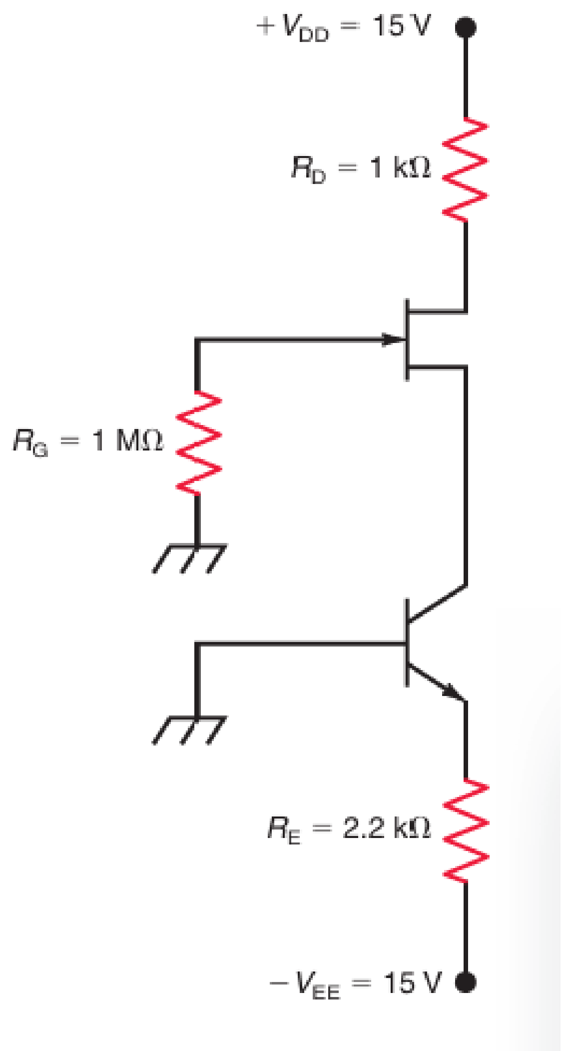
$$I_C = \frac{V_{EE} - V_{BE}}{R_E}$$



JFET Biasing Techniques

Sample Problem

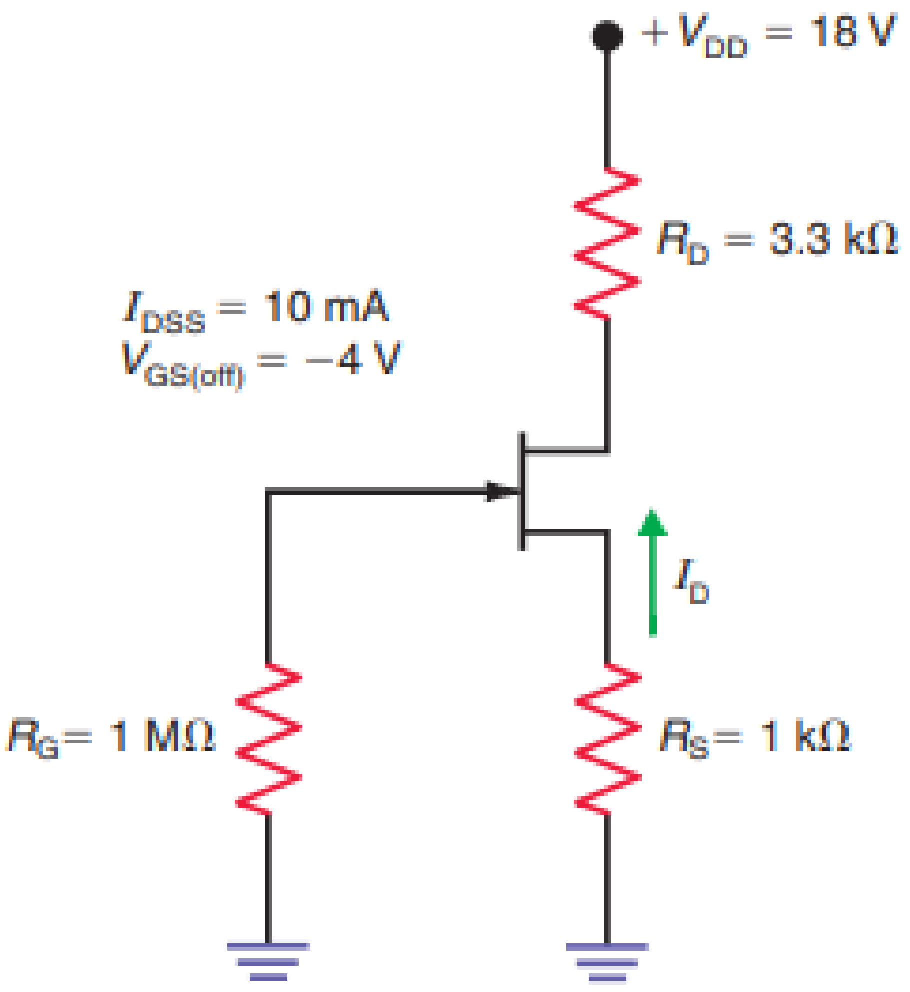
In Fig. 34, calculate the drain current, ID, and the drain voltage, VD.



JFET Biasing Techniques

Try It Yourself

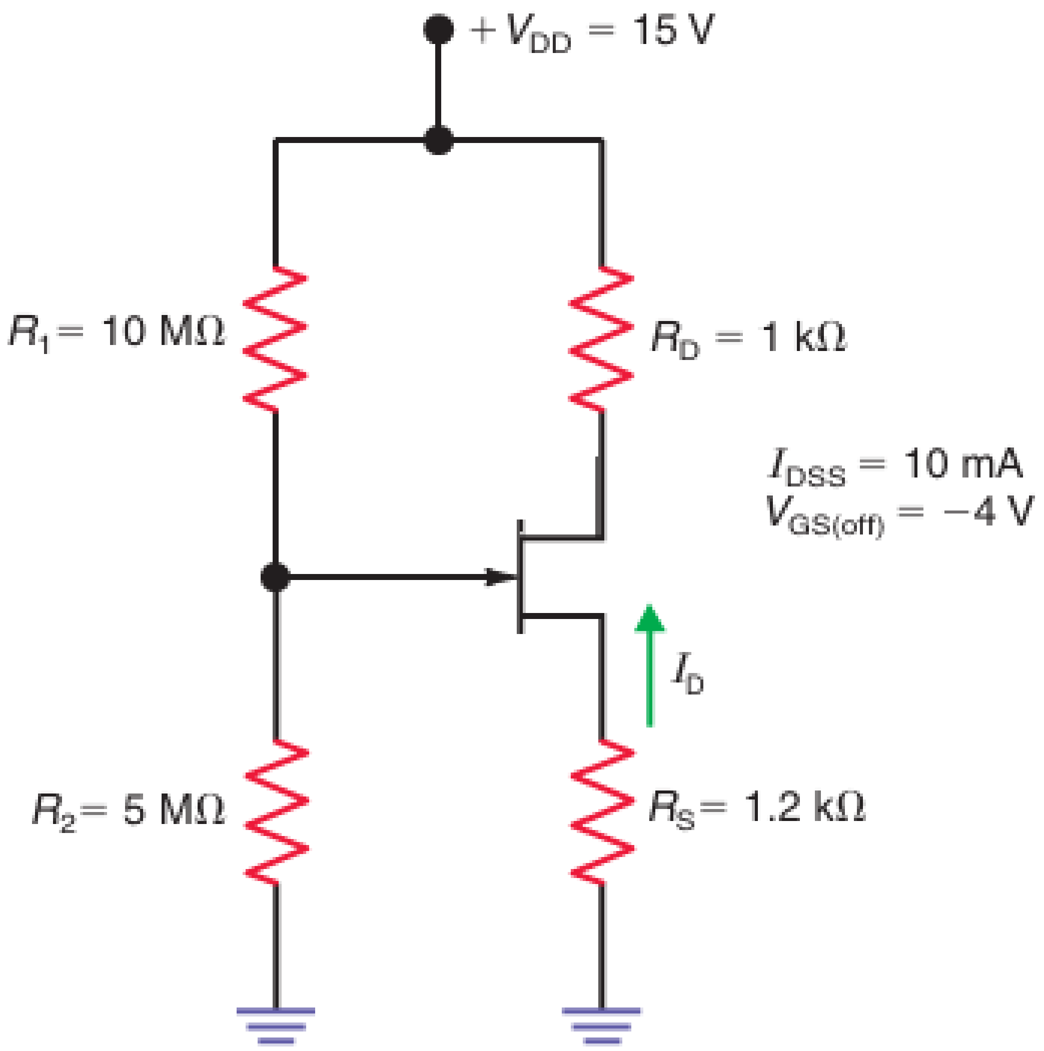
The JFET in the Figure shown has a drain current, ID, of 2.15 mA. Solve for a. VG. b. VS. c. VGS. d. VD.



JFET Biasing Techniques

Try It Yourself

If VGS = -1.15 V in the Figure shown below, solve for the following: a. VG. b. VS. c. ID. d. VD



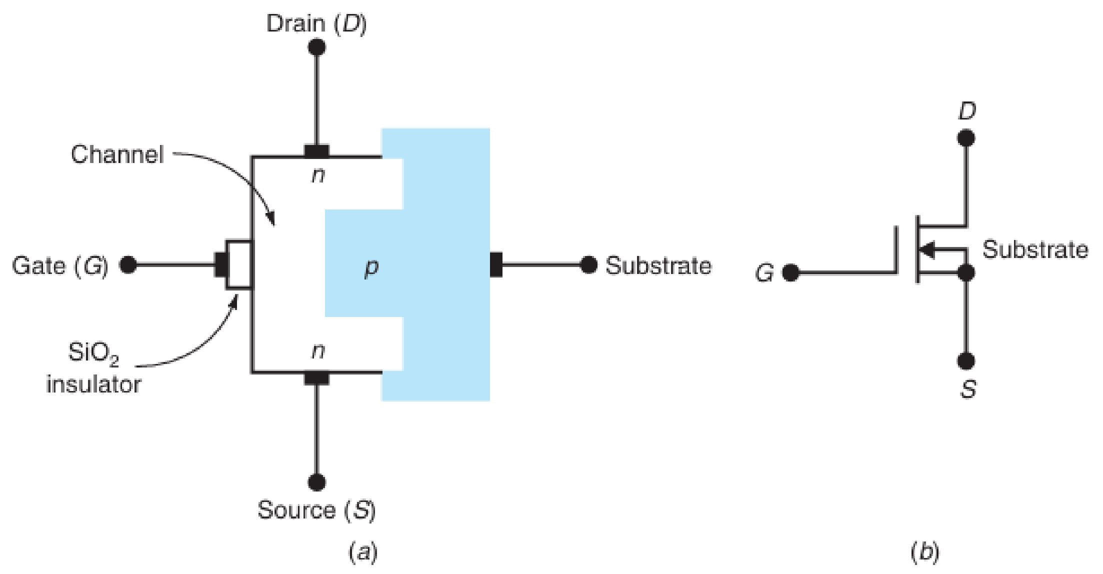
MOSFETs and Their Characteristics

The metal-oxide-semiconductor field effect transistor has a gate, source, and drain just like the JFET. Like a JFET, the drain current in a MOSFET is controlled by the gate source voltage VGS . There are two basic types of MOSFETs: the enhancement-type and the depletion-type. The enhancement-type MOSFET is usually referred to as an E-MOSFET, and the depletion-type MOSFET is referred to as a D-MOSFET. The key difference between JFETs and MOSFETs is that the gate terminal in a MOSFET is insulated from the channel. Because of this, MOSFETs are sometimes referred to as insulated gate FETs or IGFETs. Because of the insulated gate, the input impedance of a MOSFET is many times higher than that of a JFET.

MOSFETs and Their Characteristics

Depletion-Type MOSFET

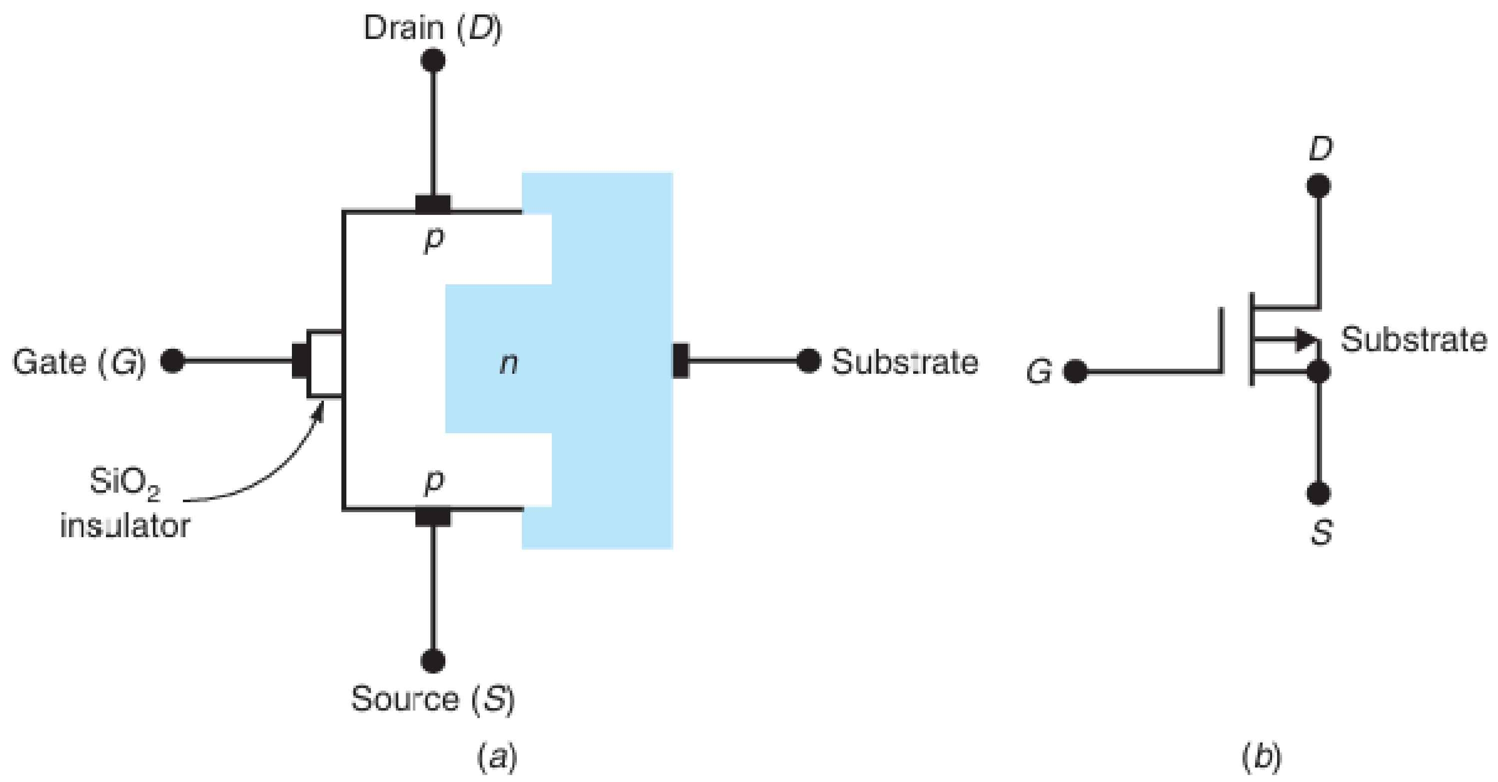
Figure 35a shows the construction of an n -channel depletion-type MOSFET, and Fig. 35b shows the schematic symbol. In Fig. 35a, the drain terminal is at the top of the n -material and the source terminal is at the bottom. The block of p -type material forms the substrate into which the n -type material is embedded. The n -type material forms the channel. Along the n -channel, a thin layer of silicon dioxide (SiO2) is deposited to isolate the gate from the channel. From gate to channel are the metal, silicon dioxide, and n -type semiconductor materials, in that order, which give the MOSFET its name. Notice in Fig. 35b that the substrate is connected to the source. This results in a three-terminal device. The solid line connecting the source and drain terminals indicates that depletion-type MOSFETs are "normally on " devices, which means that drain current fl ows when the gate-source voltage is zero.



MOSFETs and Their Characteristics

p -Channel Depletion-Type MOSFET

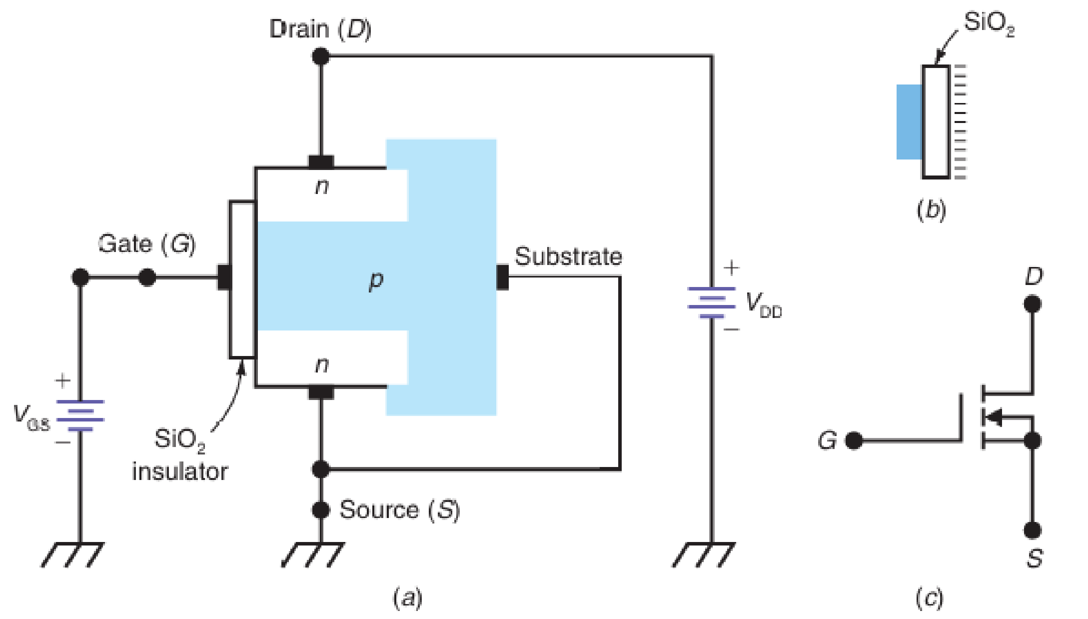
Figure 36 shows the construction, schematic symbol, and transconductance curve for a p -channel depletion-type MOSFET. Figure 36a shows that the channel is made of p -type semiconductor material and the substrate is made of n -type semiconductor material. Because of this, p -channel depletion-type MOSFETs require a negative drain voltage. Figure 36b shows the schematic symbol. Notice that the arrow points out ward away from the p -type channel.



MOSFETs and Their Characteristics

Enhancement-Type MOSFETs

Figure 37a shows the construction of an n -channel enhancement-type MOSFET. Notice that the p -type substrate makes contact with the SiO2 insulator. Because of this, there is no channel for conduction between the drain and source terminals. Notice the polarities of the supply voltages in Fig. 37a. The drain and gate are made positive with respect to the source. With VGS = 0 V, there is no channel between the source and drain and so the drain current, ID, is zero. To produce drain current, the positive gate voltage must be increased. This at tracts electrons along the right edge of the SiO2 insulator, as shown in Fig. 37b. The minimum gate-source voltage that makes drain current flow is called the thresh old voltage, designated VGS(th). When the gate voltage is less than VGS(th), the drain current, ID, is zero. The value of VGS(th) varies from one E-MOSFET to the next. Figure 37c shows the schematic symbol for the n -channel enhancement type MOSFET. Notice the broken channel line. The broken line represents the " off " condition that exists with zero gate voltage. Because of this characteristic, enhancement-type MOSFETs are called "normally off " devices.



Diode Applications

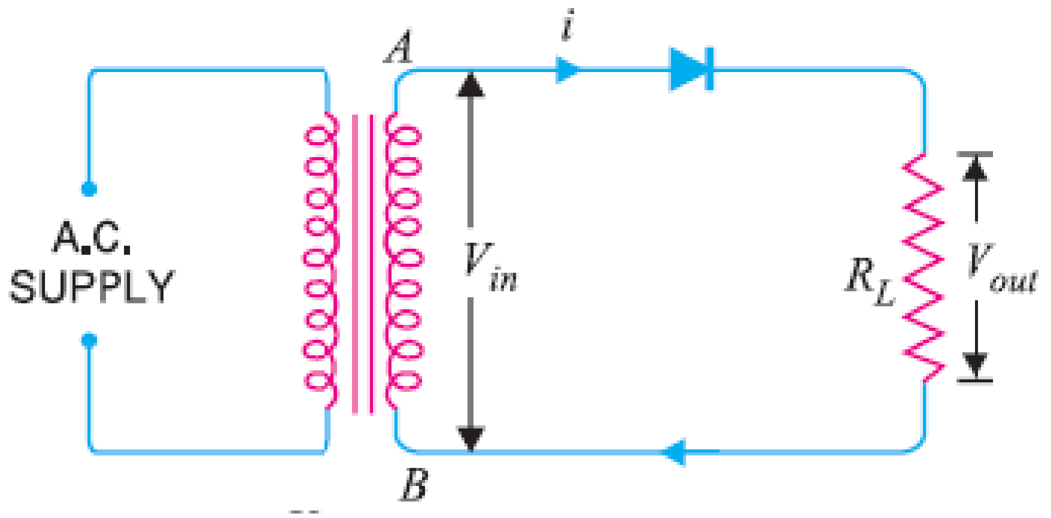
Rectification

Rectification is the process of transforming alternating current (AC) into direct current (DC), essential for powering most electronic devices since they typically require stable DC power.

Types of Rectifier

Half Wave Rectifier

Uses a single diode to convert only one half of the AC signal into DC. However, it's inefficient as it discards half of the AC wave.

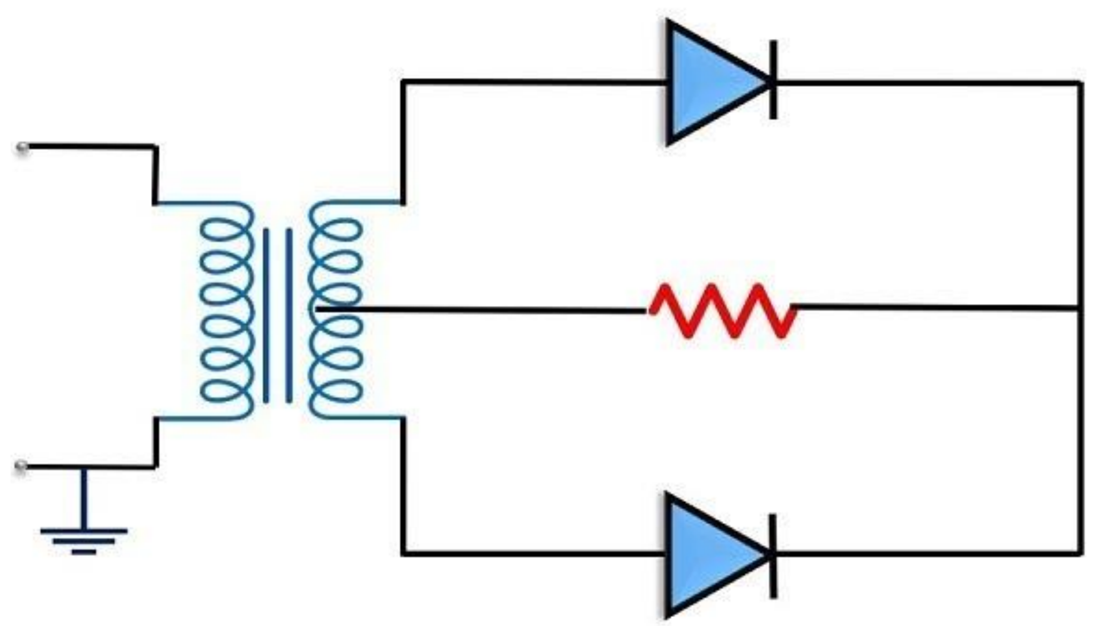


Diode Applications

Types of Rectifier

Full Wave Rectifier

Uses multiple diodes (usually four in a bridge configuration) to convert both halves of the AC signal, resulting in more efficient and smoother DC output.

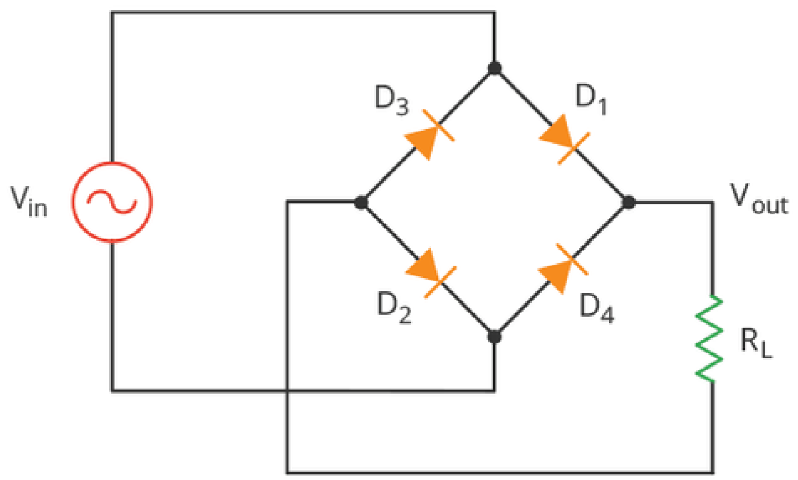


Diode Applications

Full Wave Bridge Rectifier

- Operation: The bridge rectifier circuit consists of four diodes arranged so that regardless of the polarity of the AC input, the output will always flow in one direction, effectively converting both the positive and negative halves of the AC waveform into DC.

- AC to DC Conversion: After rectification, the AC signal becomes pulsating DC. This output can be further smoothed by connecting a capacitor across the output, which filters out the AC ripple and produces a more stable DC output.



Diode Applications

Clipping and Clamping Circuits

Clipping:

A clipping circuit utilizes diodes to restrict or “clip” a signal to a certain voltage level, preventing it from exceeding a set threshold.

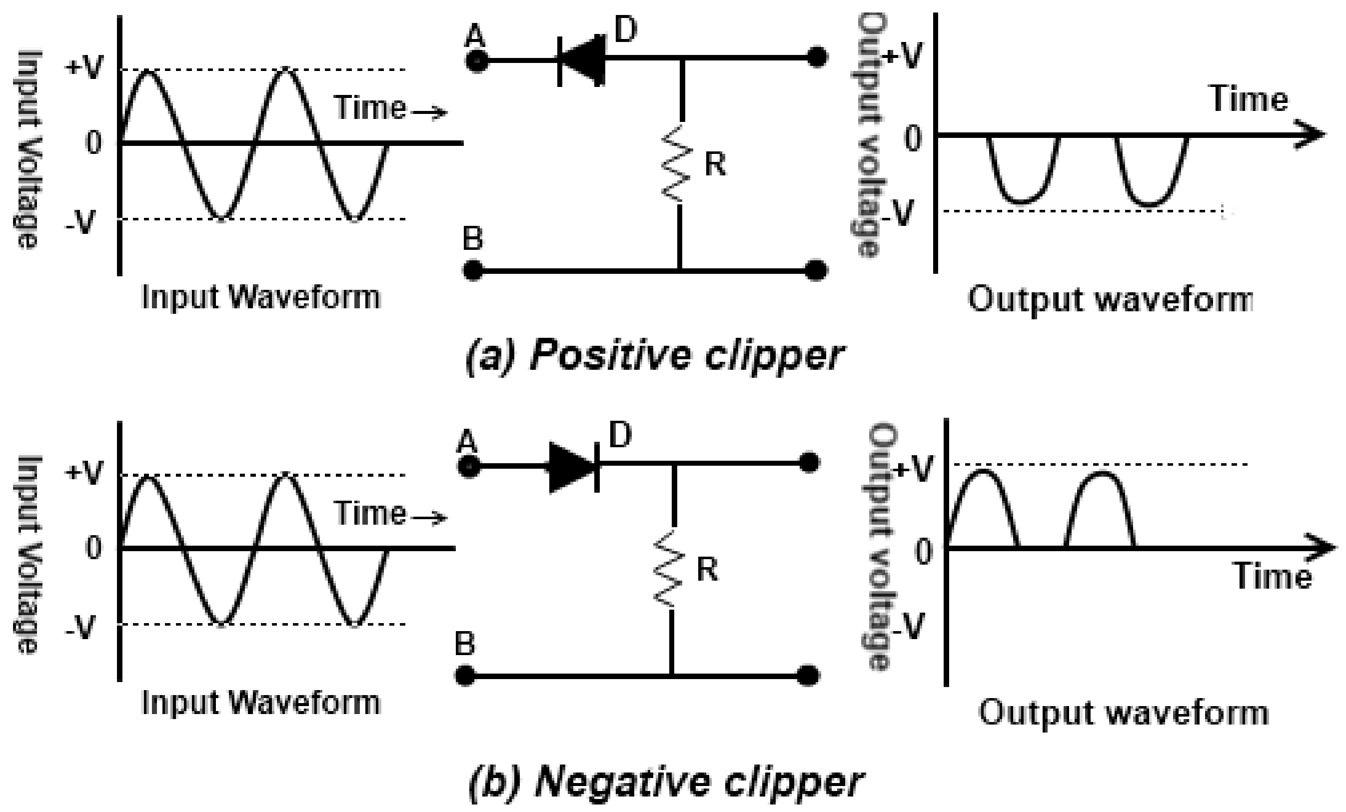
Purpose: This is particularly useful for protecting sensitive electronics from voltage spikes or for shaping waveforms in signal processing.

Diode Applications

Types of Clippers:

- Positive Clipper: Clips the positive portion of a waveform to a desired level, allowing only the negative part to pass if the threshold is set accordingly.

- Negative Clipper: Clips the negative portion of a waveform, letting the positive part remain unaffected.



Diode Applications

Clamping:

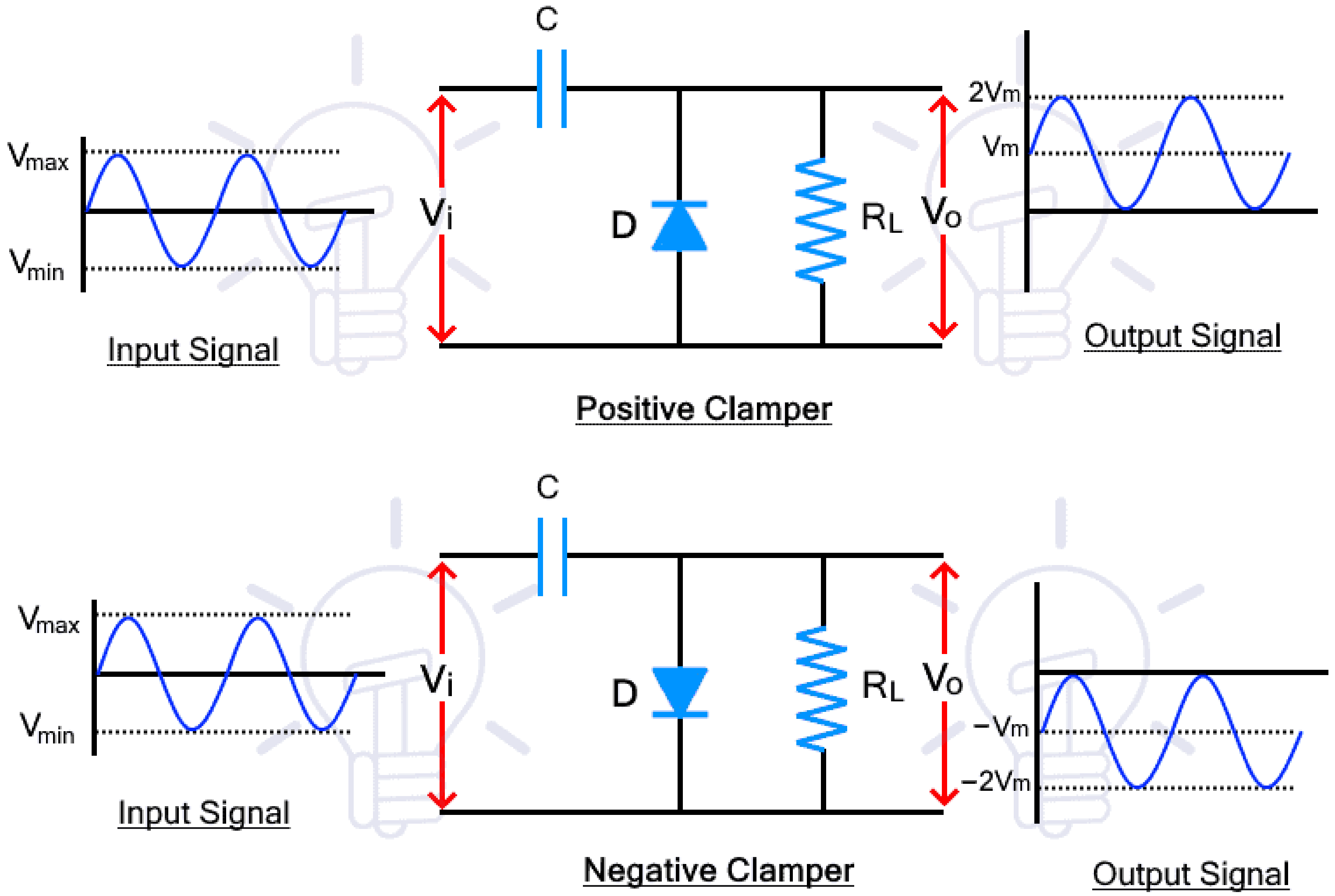
Clamping circuits, also known as DC restorers, use diodes to shift the baseline of a waveform to a specific DC level without altering the shape of the signal.

Purpose: Clamping circuits add or subtract a DC level to the input signal, which is useful for ensuring signals fall within required voltage ranges for further processing or interpretation.

Diode Applications

Types of Clamping:

- Positive Clamper: Lifts the entire waveform to a more positive level.
- Negative Clamper: Shifts the entire waveform to a more negative level.



Transistor Applications

Switching in Digital Circuits

- Role in Logic Gates: Transistors are fundamental components of logic gates, which form the core of digital circuitry. In these circuits, transistors switch between ON (1) and OFF (0) states to represent binary data, allowing computers to process complex operations.

- MOSFETs in CMOS Technology: Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) are widely used in Complementary Metal-Oxide-Semiconductor (CMOS) technology, which powers most digital ICs in computers, smartphones, and other IT devices.

- High-Speed Processing: The rapid switching ability of transistors enables processors to perform billions of calculations per second. In a processor, billions of transistors operate in tandem, allowing the execution of complex programs and multitasking.

Transistor Applications

Example of Switching in Memory Devices:

- Flash Memory: Non-volatile flash memory relies on transistors to retain data even without power. Each memory cell includes a transistor that stores a binary value, providing reliable data storage in USB drives, SSDs, and other storage devices.

- Application in IT: Transistors enable the efficient storage, retrieval, and processing of data, making them essential in applications from high-performance computing to portable electronics.

Transistor Applications

Amplification in Signal Processing

- Analog Signal Amplification: Bipolar Junction Transistors (BJTs) are commonly used in analog circuits to amplify weak signals, such as audio or radio frequency (RF) signals, making them suitable for IT applications that require audio and communication processing.

- BJTs in Amplifier Circuits: In a BJT amplifier, a small input signal at the base terminal is amplified into a much larger output signal at the collector terminal. This process is crucial for strengthening audio signals in devices like microphones, radios, and speakers.

- Power Amplification in IT Systems: In communications and data transmission systems, power amplification is vital to transmitting data signals over long distances or through different mediums without loss of quality.

Transistor Applications

Voltage Regulation and Power Management

- Voltage Regulation in Processors: Field-Effect Transistors (FETs) are essential in regulating voltage levels within IT devices. They manage power distribution in components like processors, memory, and storage devices, ensuring stable operation.

- Power MOSFETs: Power MOSFETs, designed for handling high voltages and currents, are widely used in power management systems, particularly in power supplies for computers and servers.

- Dynamic Voltage and Frequency Scaling (DVFS): In many IT applications, especially in CPUs and GPUs, MOSFETs enable DVFS. This technique dynamically adjusts voltage and frequency based on processing demand, optimizing power efficiency and reducing heat generation.

References

Grobs Basic Electronics (2010)

Electronic Devices by Thomas Floyd

ECE Superbook by Jason Ampoloquio

END