Diode and Bipolar Transistor Circuits 2

2.1 A Brief Review of Semiconductors

Semiconductors are crystalline structures in which each atom shares its valance electrons with the neighboring atoms. The simple two-dimensional crystalline structure in Fig. 2.1 shows every silicon atom sharing four valance electrons with neighboring four atoms. This is an intrinsic semiconductor which does not contain any impurities.

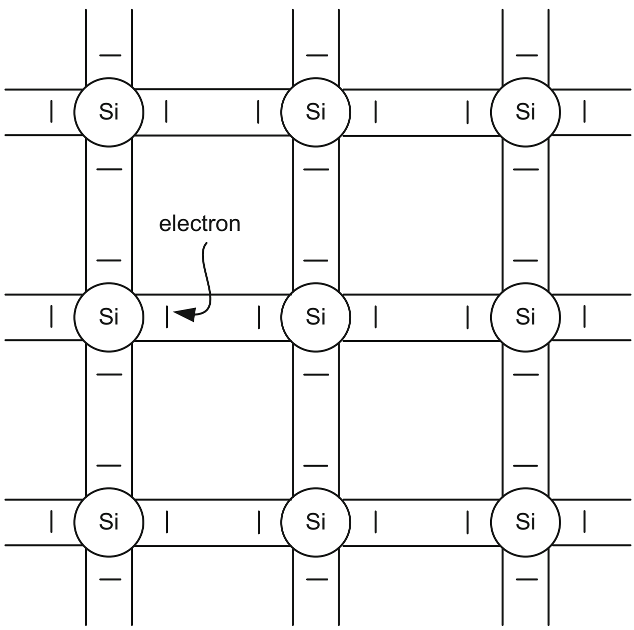

Fig. 2.1 Intrinsic semiconductor

A. Bindal, *Electronics for Embedded Systems*,
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However, if a different type of atom, such as arsenic, with five valance band electrons is placed in intrinsic silicon, the crystalline structure changes: As atom occupies a site by sharing four of the five valence electrons with Si atoms, and releases the last valance electron to the crystal as a free electron as shown in Fig. 2.2. As soon as this free electron departs from the As site, the site becomes positively charged because of the extra proton in the As atom. This crystalline structure is called N-type extrinsic semiconductor because the structure contains extra electrons and negatively charged.

If an atom with three electrons, such as boron, is introduced in intrinsic semiconductor instead of As, B atom shares all of its three valance electrons with neighboring Si atoms. The crystalline structure ultimately forms a “hole” in the boron site, signifying absence of electrons as shown in Fig. 2.3. This is called P-type semiconductor where the B site is charged negatively when the hole is occupied by a free electron.

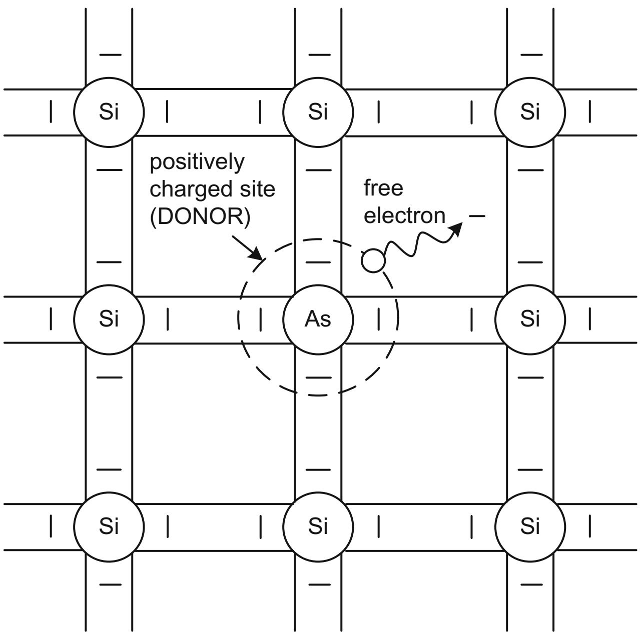


Fig. 2.2 N-type extrinsic semiconductor

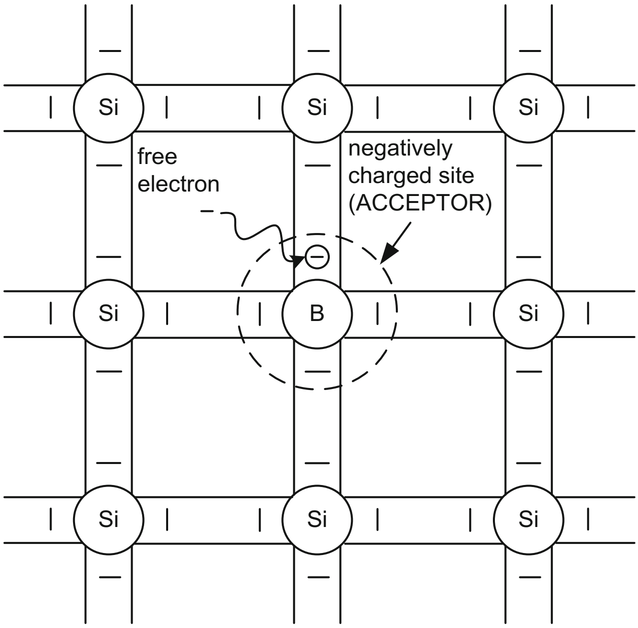


Fig. 2.3 P-type extrinsic semiconductor

Figure 2.4 shows the simplified energy band diagrams of all three types of semiconductors. An electron at the valance band, E_V, needs to have enough energy to transition to the conduction band, E_C, in order to be a free electron in the crystalline structure. This energy difference between E_C and E_V is called band gap energy, E_G. There is also a virtual energy level called Fermi level, E_F, where there is only 50% probability of finding an electron. In N-type semiconductors, the probability of finding free electrons is higher. Therefore, E_F is closer to E_C. However, this probability decreases if the semiconductor is the P-type where there are not many free electrons. As a result E_F approaches to E_V.

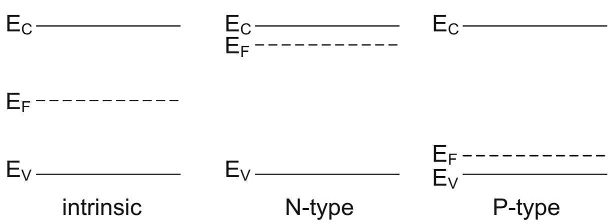


Fig. 2.4 Intrinsic, N-type and P-type semiconductor energy band diagrams

2.2 PN Junction

When N-type and P-type semiconductors are joined there will be an initial flow of electrons from the N-type semiconductor to the P-type until the Fermi energy levels on both sides become equal, and the structure becomes stable. Both the conduction and valance bands close to the junction bend as the result of the initial electron flow as shown in Fig. 2.5.

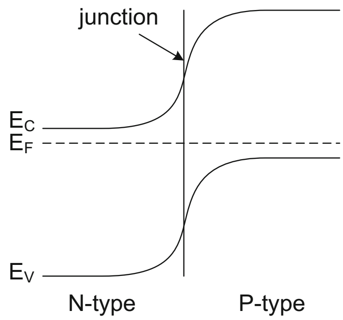


Fig. 2.5 PN junction

If a forward voltage, V_F, is applied to the PN junction in the direction shown in Fig. 2.6, the energy supplied to the junction, $E = -qV_F$, moves the Fermi level of the N-type semiconductor upwards relative to the P-type until the conduction and valence bands almost become flat across the junction. The applied voltage pushes the electrons in the N-type semiconductor and the holes in the P-type semiconductor towards each other, resulting in a continuous flow of current.

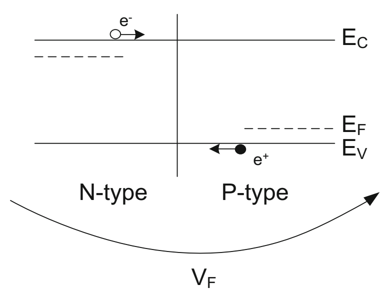


Fig. 2.6 PN junction under forward bias

When a reverse voltage, V_R, is applied to the junction, on the other hand, electrons in the N-side and holes in the P-side are extracted from the PN junction, resulting in no conduction current as shown in Fig. 2.7.

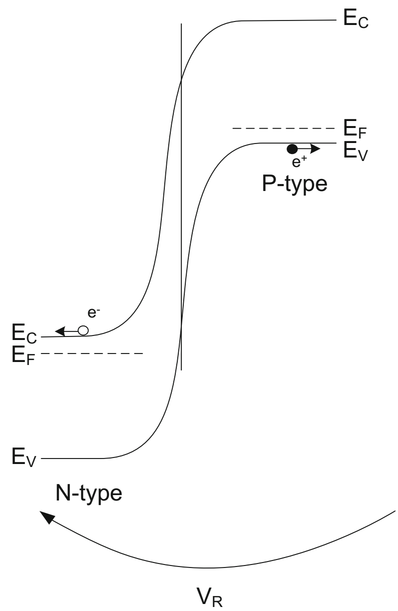


Fig. 2.7 PN junction under reverse bias

When we plot the forward PN junction current as a function of forward voltage, the current increases slightly before the applied voltage reaches V_F as shown in Fig. 2.8. However, this current keeps increasing exponentially in the neighborhood of V_F as it abides by the following equation:

$$I_F = I_o\left[\mathbf{exp}\left(\frac{qV_F}{kT}\right) - 1\right] \tag{2.1}$$

In this equation, q is called the electronic charge, k is the Boltzmann constant, T is temperature, and I_o is the leakage current.

Applying reverse voltage across the diode produces only a small leakage current until the junction breaks down at V_{BR} and becomes a short circuit.

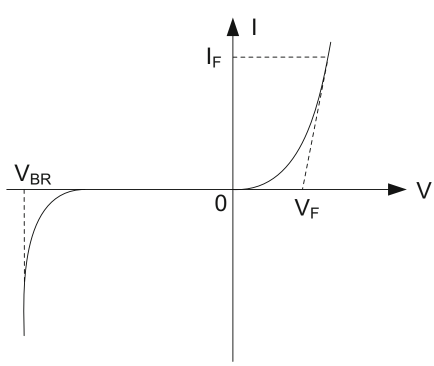


Fig. 2.8 PN junction diode current-voltage (I-V) characteristics

2.3 Rectifying Diode Circuits

The simplest diode circuit incorporates a series resistor with the diode as shown in Fig. 2.9. In this circuit, the output voltage, V_{OUT}, clamps to V_F which is approximately equal to 0.7 V for silicon. The current, I_D, becomes equal to:

$$I_D = \frac{(V_{CC} - 0.7)}{R_D} = I_F \tag{2.2}$$

We need to use an appropriate R_D to limit the forward current through the diode according to the manufacturer's specifications.

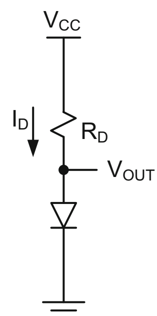


Fig. 2.9 Biasing circuit for a rectifying diode

A half-wave rectifier shown in Fig. 2.10 is an extension of the simple diode circuit in Fig. 2.9. When a sinusoidal waveform is applied to the input of this circuit as shown in the top part of Fig. 2.11, the diode will only conduct if the input voltage becomes greater than or equal to its forward voltage, $V_F \approx 0.7$ V. Therefore, when the input reaches its peak value, V_{MAX}, the output can only produce (V_{MAX} − 0.7) as shown by the center waveform in Fig. 2.11.

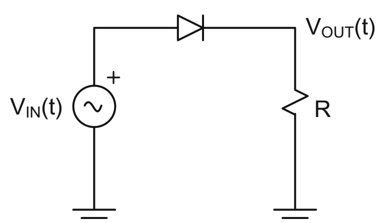


Fig. 2.10 Half-wave rectifier circuit

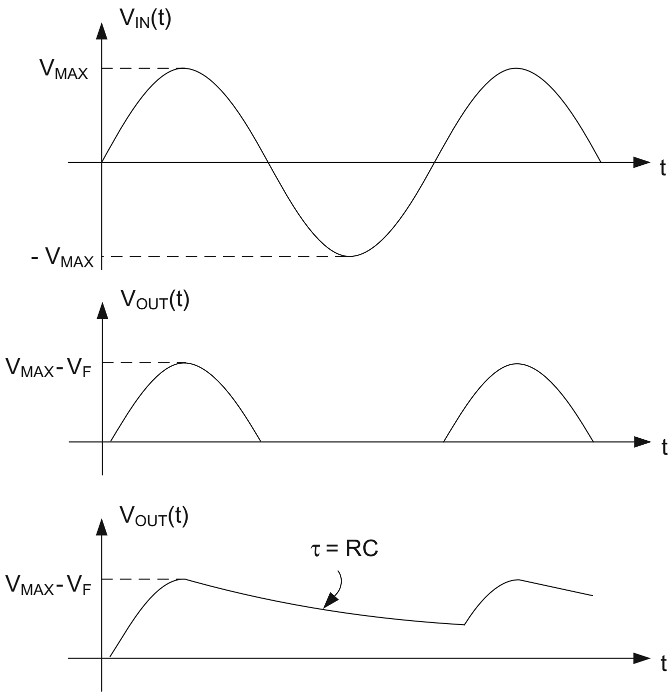


Fig. 2.11 Sinusoidal input (*top*), half-wave rectifier output (*mid*), output with capacitor (*bottom*)

However, the real purpose of this circuit is to produce an "almost" constant voltage by eliminating the half sinusoids as shown by the bottom waveform in Fig. 2.11. This can be achieved by connecting a parallel capacitor to the output resistor as shown in Fig. 2.12. When the input climbs from 0 V towards V_{MAX}, the output closely follows the input as in the bottom waveform of Fig. 2.11. However, as the input starts decreasing from V_{MAX} to 0 V, the voltage across the capacitor can no longer follow this change. The previously stored voltage across the capacitor (V_{MAX} in this case) becomes larger than the input voltage, reverse-biasing the diode, and stopping the current conduction. As a result, the capacitor starts discharging through the resistor with a time constant, RC, as shown in the bottom part of Fig. 2.11.

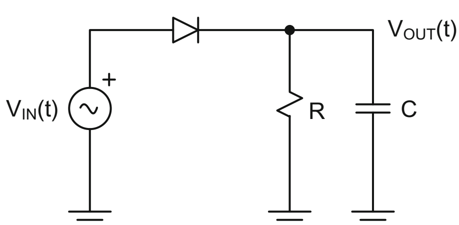


Fig. 2.12 Half-wave rectifier circuit with output capacitor

The full-wave rectifier composed of four diodes is shown in Fig. 2.13. The circuit output is measured across the resistor, R. When the polarity of the sinusoidal input voltage is in its positive phase, the current conducts through two diodes in series and the output resistor as shown by the equivalent circuit on the left hand side of Fig. 2.14. As a result, the output voltage follows the input, but becomes (V_{IN} − $2V_F$) as shown by the center waveform in Fig. 2.15.

When the sinusoidal input voltage changes its phase to negative, current conduction through the circuit still exists. But, this time the other two diodes start conducting as shown by the equivalent circuit on the right hand side of Fig. 2.14. The voltage drop across the output resistor still becomes equal to (V_{IN} − $2V_F$).

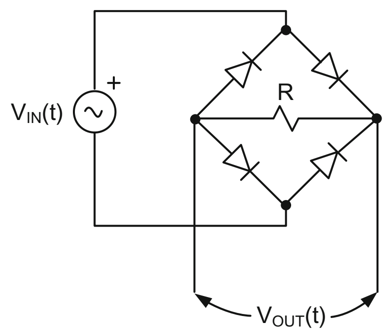


Fig. 2.13 Full-wave rectifier circuit

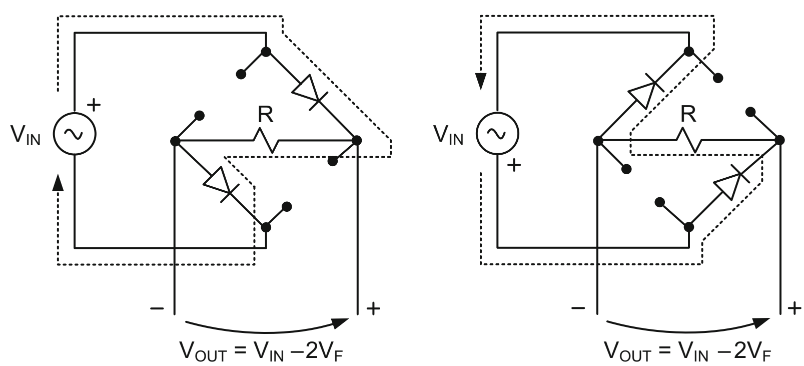


Fig. 2.14 Full-wave rectifier circuit in positive phase (*left*), in negative phase (*right*)

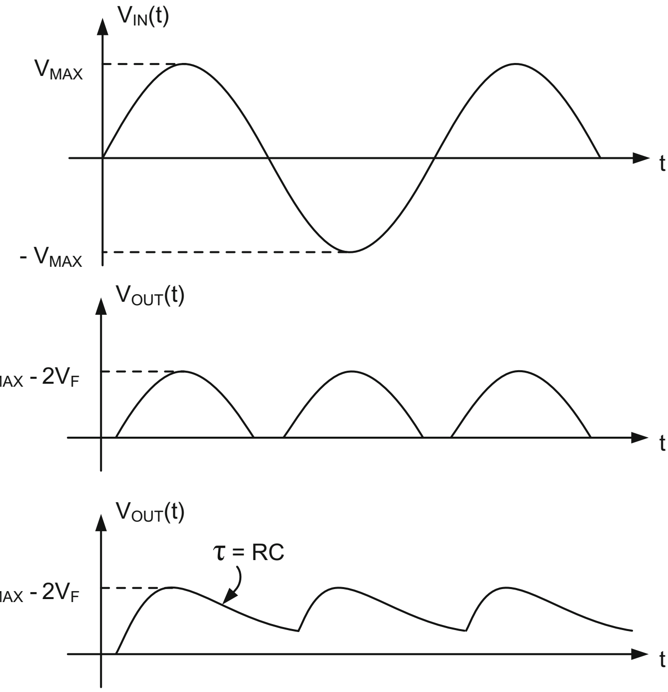


Fig. 2.15 Sinusoidal input (*top*), full-wave rectifier output without capacitor (*mid*), output with capacitor (*bottom*)

The Direct Current (DC) rectification is achieved by adding a parallel capacitor at the output of the full-wave rectifier shown in Fig. 2.16. This circuit reveals a more efficient mechanism in generating a DC output compared to a half-wave rectifier. The circuit behavior in full-wave rectifier is similar to half-wave rectifier: the output closely follows the input in the first and third quadrants of the sinusoidal input signal, and the current conduction stops during the second and the fourth quadrants when the capacitor discharges through the output resistor with a time constant, RC, as shown by the bottom waveform of Fig. 2.15.

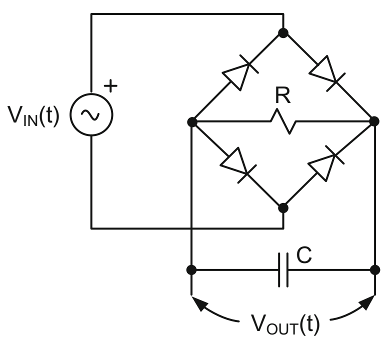


Fig. 2.16 Full-wave rectifier circuit with output capacitor

2.4 Zener Diode Circuits

Zener diode is another two terminal device where a precise constant voltage can be obtained across its terminals. Zener diode manufacturers specify the nominal and maximum Zener voltage, V_Z, and the reverse current, I_Z, in their datasheets. Zener diode is reverse biased with a series resistor that adjusts I_Z as shown in Fig. 2.17. The resistance value becomes:

$$R_Z = \frac{(V_{CC} - V_Z)}{I_Z} \tag{2.3}$$

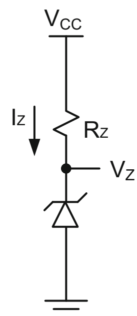


Fig. 2.17 Zener diode circuit

2.5 Light Emitting Diode (LED)

Light Emitting Diode (LED) is an optoelectronic device that emits light at a specific wavelength when an appropriate bias current, I_L, is applied as shown in Fig. 2.18. R_L is adjusted in order to compute I_L, and comply with the required luminosity.

$$R_L = \frac{(V_{CC} - V_L)}{I_L} \tag{2.4}$$

The voltage drop across LED, V_L, is also specified in the manufacturer's datasheet.

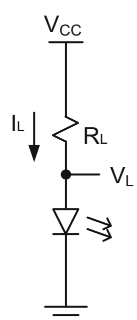


Fig. 2.18 LED diode circuit

2.6 Bipolar Transistors

There are two kinds of bipolar junction transistors (BJT) used in electronic circuits: NPN and PNP. The equivalent circuit of an NPN transistor shown in Fig. 2.19 basically consists of two back-to-back diodes. Its emitter current is the sum of base and collector currents as shown in Eq. 2.5

$$I_E = I_B + I_C \tag{2.5}$$

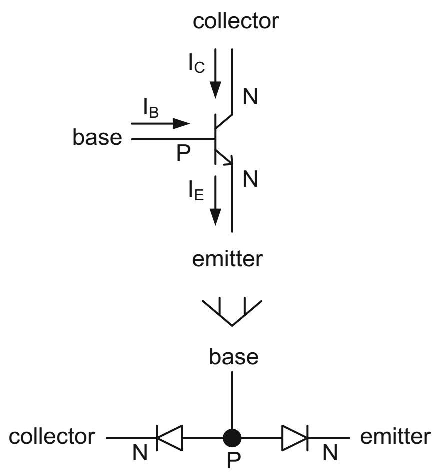


Fig. 2.19 NPN bipolar transistor and its equivalent circuit

The second type of BJT is the PNP transistor shown in Fig. 2.20. Its emitter current is still the sum of collector and base currents. However, the currents in this transistor flow in completely opposite directions compared to the currents in an NPN transistor.

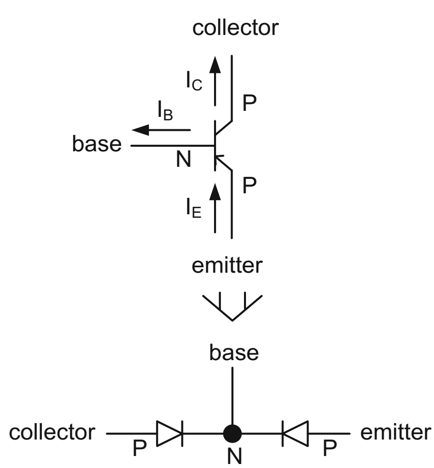


Fig. 2.20 PNP bipolar transistor and its equivalent circuit

The current-voltage relationship of a typical NPN transistor is shown in Fig. 2.21. In this figure, collector current, I_C, is plotted as a function of collector-emitter voltage, V_{CE}, for a set of base currents, I_B. For each I_B, I_C initially increases exponentially with V_{CE} until it reaches a point after which it essentially remains constant.

The current-voltage characteristics in Fig. 2.21 show three different regions of transistor operation. The first region is the cut-off region where the transistor does not conduct at all, and its base and collector currents become essentially 0 A. The second region is the active region where I_C remains almost constant between $V_{CE} \approx 0.2$ V and V_{CC}. The third region is the saturation region where I_C exponentially increases with V_{CE} between 0 and 0.2 V.

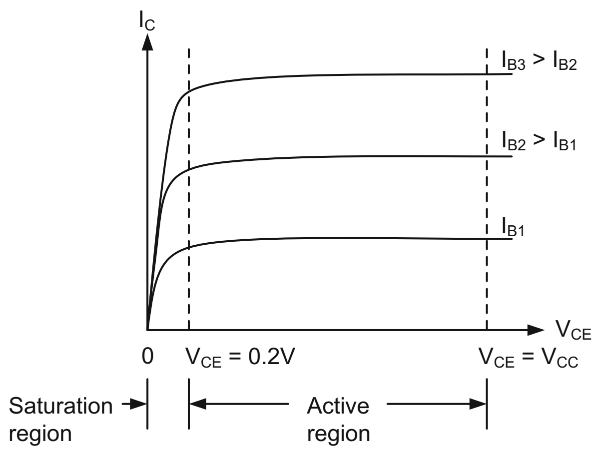


Fig. 2.21 Current-voltage characteristics of an NPN transistor for different base current values

In cut-off mode of operation, the transistor stops conducting because the voltage across its base-emitter junction drops below 0.7 V, and its collector base-junction becomes reverse biased as shown in Fig. 2.22. As a result, only leakage currents exist in the transistor; I_B and I_C essentially become 0 A.

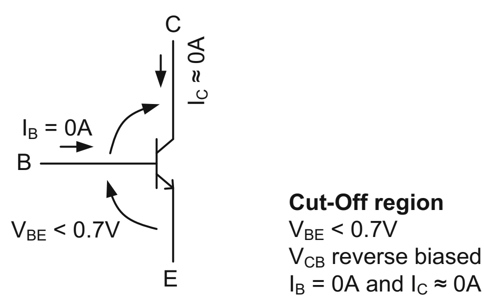


Fig. 2.22 Transistor bias currents and voltages in cut-off mode of operation

When the transistor operates in active mode, its base-emitter junction voltage, V_{BE}, becomes approximately equal to 0.7 V although its collector-base junction still remains reverse biased. The base and collector currents become proportional to each other with a current gain of β (or h_{FE} according to some transistor manufacturers) as shown in Fig. 2.23.

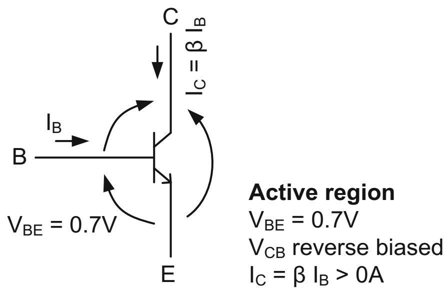


Fig. 2.23 Transistor bias currents and voltages in active mode of operation

When the transistor finally reaches saturation region, its collector-base and emitter-base junctions become forward biased as shown in Fig. 2.24. The transistor remains in saturation as long as V_{BE} is greater than 0.7 V. A typical V_{BE} and V_{BC} are approximately 0.8 and 0.6 V, respectively. This produces 0.2 V between collector and emitter terminals as shown in the figure. In this mode, I_B and I_C can no longer hold the linear relationship ($I_C = \beta I_B$). A new relationship forms between the base saturation current, I_{BSAT}, and the base active-region current, I_{BACT}: $I_{BSAT} >> I_{BACT}$. This, in turn, produces $I_{BSAT} >> (I_{CACT}/\beta)$. Here, I_{CACT} is the active-region collector current.

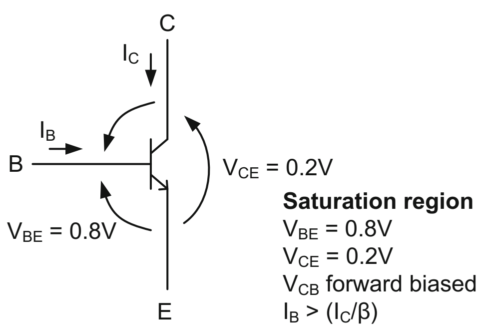


Fig. 2.24 Transistor bias currents and voltages in saturation mode of operation

2.7 Bipolar Transistor Circuits

This section is dedicated to using BJTs in simple circuits, and analyzing the circuit behavior when the transistor is in active and saturation regions.

Example 2.1 A simple NPN bipolar transistor circuit that consists of an NPN bipolar transistor, R_B and R_C is given in Fig. 2.25. If V_{CC} = 15 V, V_{IN} = 5 V and β = 100, calculate I_B, I_C. What mode will this transistor operate in?

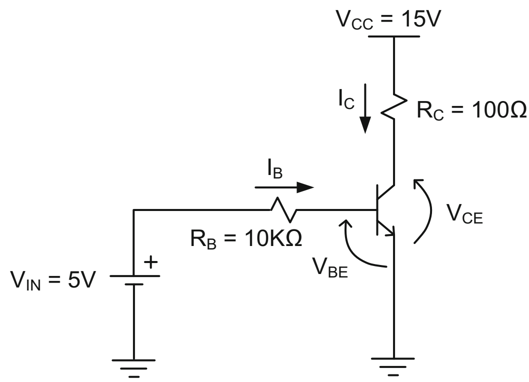


Fig. 2.25 A simple NPN bipolar circuit

The first task is to write Kirchoff's Voltage Law (KVL) around the BE and CE junctions as shown in Eqs. 2.6 and 2.7. Therefore,

$$V_{IN} = R_B I_B + V_{BE} \tag{2.6}$$

$$V_{CC} = R_C I_C + V_{CE} \tag{2.7}$$

Test for cut-off mode:

Set $I_B = I_C = 0$ A. This produces V_{BE} = 5 V and V_{CE} = 15 V, and it proves that the transistor does not operate in cut-off region.

Test for active mode, set V_{BE} = 0.7 V and solve I_B from Eq. 2.6. Thus,

$$I_B = \frac{(V_{IN} - V_{BE})}{R_B} = \frac{(5 - 0.7)}{10\,K\Omega} = 0.43\,mA$$

Then,

$I_C = \beta\ I_B$ = 100 (0.43 mA) = 43 mA. Substitute I_C = 43 mA into Eq. 2.7 and solve for V_{CE}. Thus,

$V_{CE} = V_{CC} - R_C\ I_C$ = 15 − 0.1 KΩ (43 mA) = 15 − 4.3 = 10.7 V

This value is greater than 0.2 V and proves that the transistor operates in the active region as shown in Fig. 2.26. In this figure, Eq. 2.7 is superimposed on top of the transistor I_C-V_{CE} characteristics in order to show where exactly this transistor operates at (quiescent point, Q).

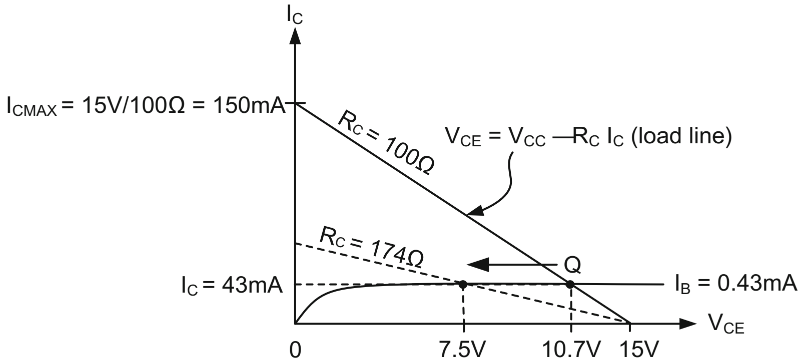


Fig. 2.26 The quiescent point of the transistor

However, the location of the Q point is not optimal in this figure, and as it needs to be closer to the midpoint between 0 and V_{CC} such as $V_{CEQ} = V_{CC}/2 = 7.5$ V to be more suitable for analog applications.

From Fig. 2.26, when $I_B = 0.43$ mA and $V_{CE} = 7.5$ V, I_C becomes 43 mA. Thus,

$$R_C = \frac{(V_{CC} - V_{CEQ})}{I_C} = \frac{(15 - 7.5)}{0.043} = 174\,\Omega \text{ instead of } 100\,\Omega.$$

The new load line is plotted in Fig. 2.26 with dashed lines.

Example 2.2 Another bipolar transistor circuit is given in Fig. 2.27. In this schematic, I_C is selected to be 20 mA. The circuit still uses $V_{IN} = 5$ V and $V_{CC} = 15$ V for its operation. What are the values of R_B and R_C such that this transistor operates in the middle of the active region at $V_{CEQ} = 7.5$ V?

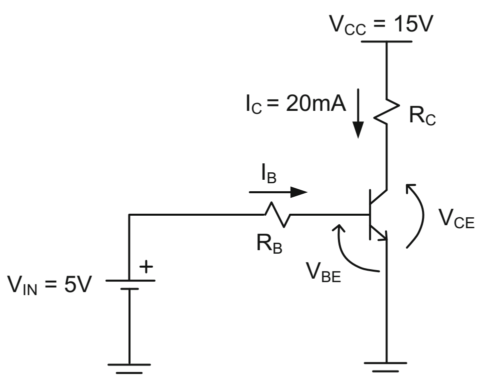


Fig. 2.27 A bipolar circuit whose $I_C = 20$ mA, but its R_C and R_B are unknown

For this design question, one must refer to the manufacturer's datasheet and fetch the transistor I_C-V_{CE} characteristics as shown in Fig. 2.28.

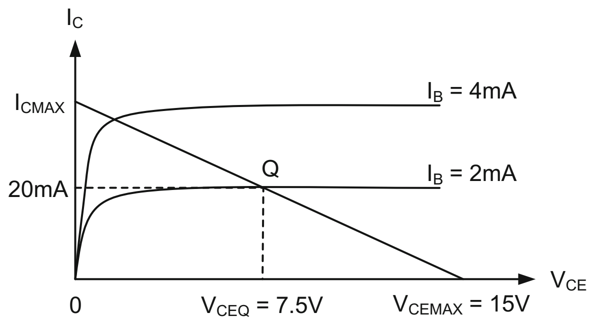


Fig. 2.28 Manufacturer's I-V characteristics of the NPN transistor

The load line from Eq. 2.7 is superimposed on top of the I_C-V_{CE} characteristics, and I_B becomes 2 mA at V_{CEQ} = 7.5 V when I_C = 20 mA. Since the transistor operates in active region, $\beta = I_C/I_B$ becomes 10. Rewriting Eq. 2.7 yields:

$$R_C = \frac{(V_{CC} - V_{CEQ})}{I_C} = \frac{(15 - 7.5)}{0.020} = 375\,\Omega$$

Rewriting Eq. 2.6 yields

$$R_B = \frac{(V_{IN} - V_{BE})}{I_B} = \frac{(5 - 0.7)}{0.002} = 2.15\,K\Omega$$

However, there may be an instance where the load line may not necessarily intersect any of the I_C-V_{CE} curves at V_{CEQ} = 7.5 V provided by the manufacturer, and the situation becomes similar to the case in Fig. 2.29. In this instance, R_C is still calculated using Eq. 2.7 since V_{CEQ} and I_{CQ} have not changed.

$$R_C = \frac{(V_{CC} - V_{CEQ})}{I_C} = \frac{(15 - 7.5)}{0.020} = 375\,\Omega$$

However, to calculate R_B we need to use β = 10 calculated earlier. Thus,

$$I_B = \frac{I_C}{\beta} = \frac{20\,mA}{10} = 2\,mA$$

Then using Eq. 2.6, R_B can be calculated as

$$R_B = \frac{(V_{IN} - V_{BE})}{I_B} = \frac{(5 - 0.7)}{0.002} = 2.15\,K\Omega$$

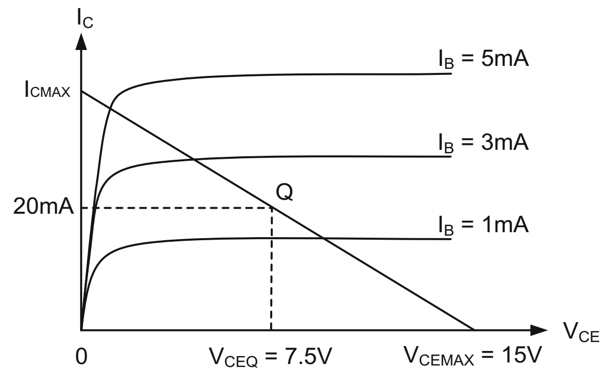


Fig. 2.29 An instance where load line does not intersect any I-V characteristics

Example 2.3 Suppose the bipolar transistor circuit in Fig. 2.27 needs to operate in the saturation region where $I_{CSAT} = 40$ mA and $V_{CESAT} = 0.2$ V. What are the values of R_B and R_C?

From Eq. 2.7, we have:

$$R_C = \frac{(V_{CC} - V_{CESAT})}{I_{CSAT}} = \frac{(15 - 0.2)}{0.040} = 370\,\Omega$$

To find R_B, we need to use Eq. 2.6. Thus,

$$R_B = \frac{(V_{IN} - V_{BE})}{I_{BSAT}} = \frac{(5 - 0.8)}{I_{BSAT}} = \frac{4.2}{I_{BSAT}}$$

In saturation, the circuit operates with the load line no.1 as shown in Fig. 2.30, producing $I_C = 40$ mA at Q_{SAT}. At this point however, I_{BSAT} is not known other than $I_{BSAT} >> I_{BACT}$. The ratio between I_{BSAT} and I_{BACT} can be set as high as 10, although this number is very conservative. A more practical the multiplication factor may be in the neighborhood of 2 or 3 depending on I_C-V_{CE} characteristics of the transistor.

Now, R_B becomes:

$$R_B = \frac{4.2}{10 I_{BACT}}$$

To find I_{BACT} in the equation above, we need to operate the transistor in the active region with the same collector current when the transistor was in saturation region. That means that I_{CACT} needs to be 40 mA, which rotates the load line clockwise around $V_{CEMAX} = 15$ V to position no. 2 so that the transistor operates in the middle of active region at $V_{CE} = 7.5$ V. At this new point, Q_{ACT}, load line no. 2 intersects only one I_B-curve: $I_B = 4$ mA. Therefore, I_{BACT} becomes 4 mA, and $I_{BSAT} = 10 I_{BACT} = 40$ mA.

Thus,

$$R_B = \frac{4.2}{I_{BSAT}} = \frac{4.2}{0.040} = 105\,\Omega$$

With R_C = 370 Ω and R_B = 105 Ω, the collector and the base currents both become 40 mA, and the transistor operates in saturation region with load line no. 1.

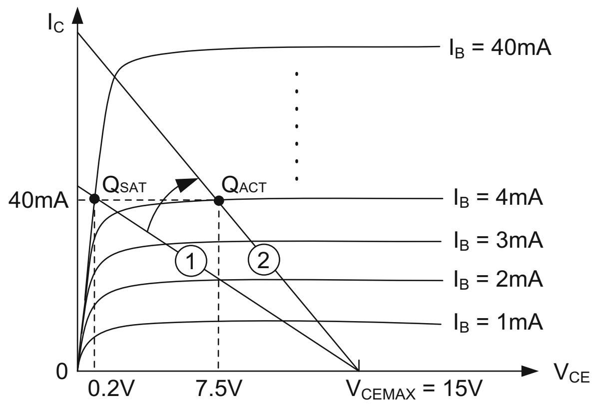
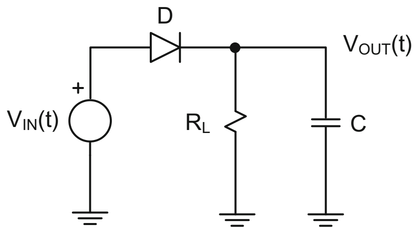
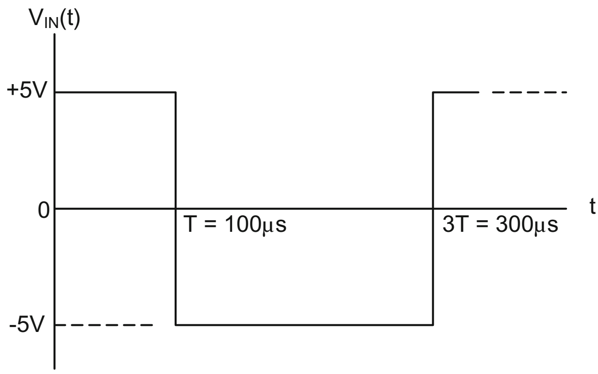


Fig. 2.30 Load line rotation to make $I_{CSAT} \approx I_{CACT}$ to allow $I_{BSAT} \gg I_{BACT}$

Review Questions

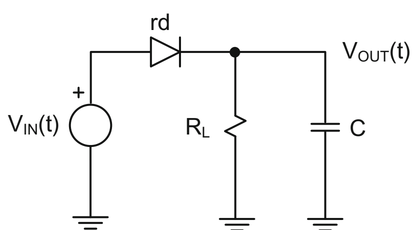
1. The following rectifier circuit is given:

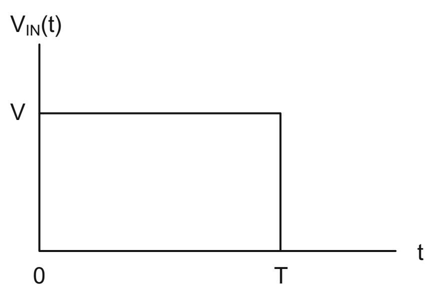




(a) If the forward-biased diode voltage is 1 V, C = 10 µF and R_L = 10 Ω (load resistance), calculate the expression for $V_{OUT}(t)$ and plot the output voltage.
(b) If R_L = 100 Ω, what is the value of C if $V_{OUT}(t)$ drops by 1 V between T = 100 µs and 3T = 300 µs?

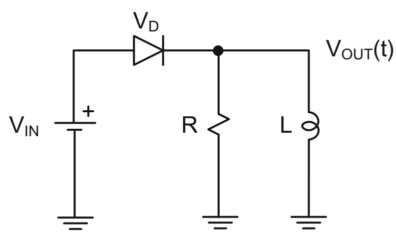
2. The following diode circuit is given:



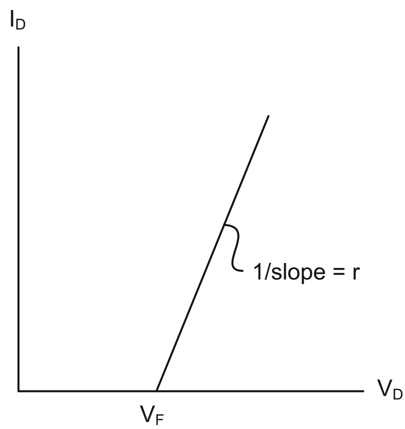


In this circuit, the equivalent resistance of the diode is rd when the diode turns on at a forward bias voltage of V_F, where V_F is much smaller compared to V for 0 < t < T. Assuming that $V_{OUT}(0) = 0$ V and the time constant of the circuit is much smaller than T, determine the output voltage, $V_{OUT}(t)$, for 0 < t < T and t > T. Natural frequencies method described in Chapter 1 may be used to obtain the equation for $V_{OUT}(t)$. Plot the output waveform.

3. The following diode circuit is given:



In this circuit above, when V_{IN} is reduced below V_F the diode turns off. The inverse slope in the I-V characteristics below gives the diode internal resistance, r.

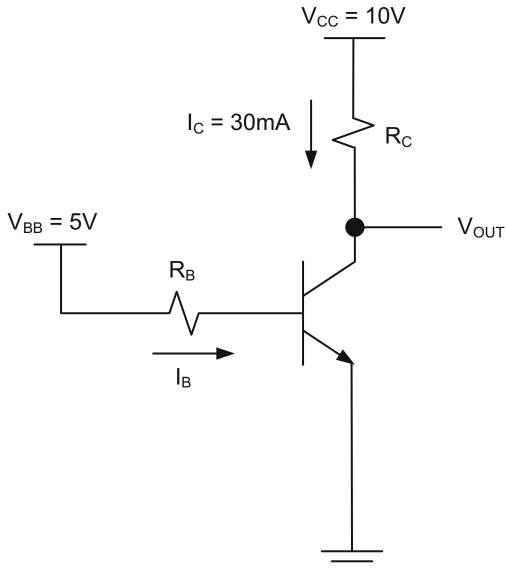


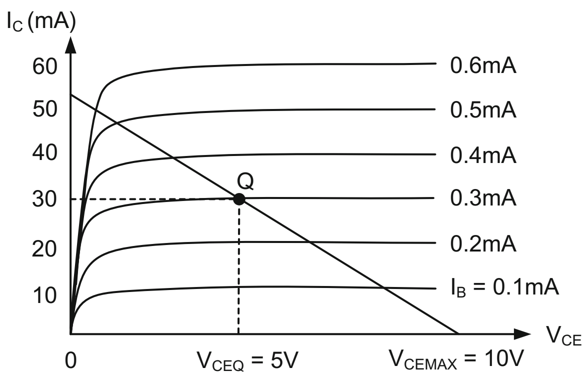
(a) Compute and plot the current through the inductor if the initial inductor current is 0 A. Either time domain analysis or natural frequencies method may be used to compute the result.

(b) Compute and plot the voltage across the output, V_{OUT}. Either time domain analysis or natural frequencies method may be used to compute the result.

4. The NPN bipolar transistor is used to operate in the middle of active region. The transistor requires a collector current, $I_C = 30$ mA, when the output of the circuit, V_{OUT}, is at 5 V. The transistor develops $V_{BE} = 0.7$ V in active region and maintains a current gain of 100, i.e. $\beta = I_C/I_B = 100$.

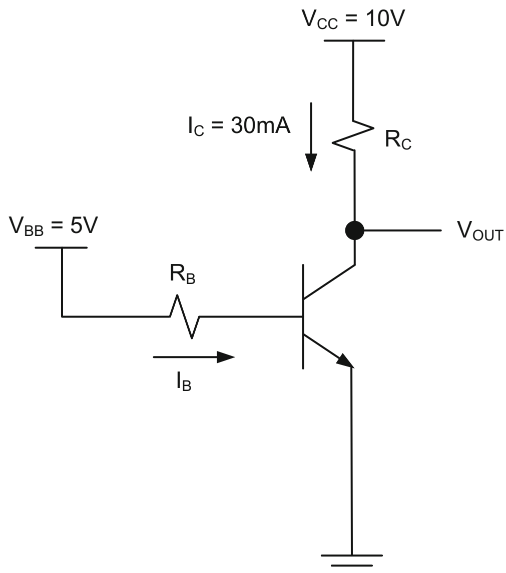
Use the output I_C-V_{CE} characteristics below to compute R_B and R_C that satisfy the proper transistor operation.

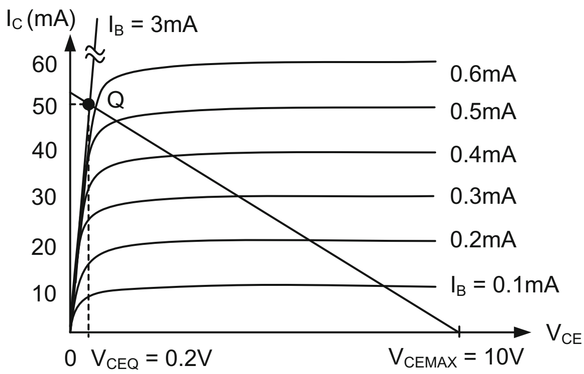




5. The same NPN bipolar transistor in question 4 now operates in saturation region where it develops $V_{BESAT} = 0.8$ V and $V_{CESAT} = 0.2$ V. It also produces a base current, I_{BSAT}, 10 times larger than the active-region base current, I_{BACT}.

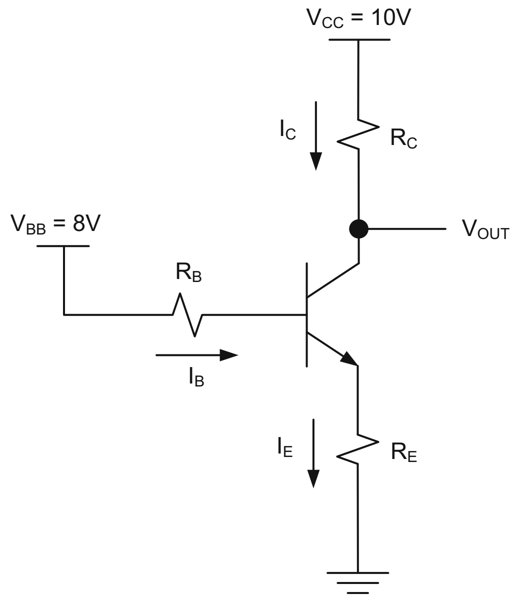
If the transistor requires a collector current, I_{CSAT} = 30 mA, to operate in saturation region, find R_B and R_C to satisfy the proper transistor operation. Use the I_C-V_{CE} characteristics below for calculations.

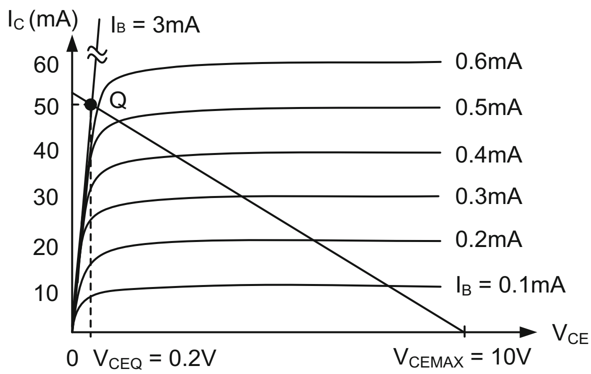




6. In the following circuit, the NPN bipolar transistor is used in such a way that it operates in the saturation region. The circuit requires a collector current, I_{CSAT} = 30 mA, when its output, V_{OUT}, is at 5 V. The transistor develops V_{BESAT} = 0.8 V and V_{CESAT} = 0.2 V in saturation region when its base current, I_{BSAT}, is set 10 times higher compared to the base current when it is in active region, I_{BACT}.

Find R_C, R_B and R_E that satisfy the proper transistor operation.





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