...points A and B.

DC Equivalent Circuits

voltage cell

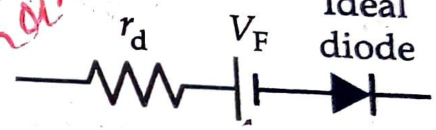
An *equivalent circuit* for a device is a circuit that represents the device behavior. Usually, the equivalent circuit is made up of a number of components, such as resistors and voltage cells. A diode equivalent circuit may be substituted for the device when investigating a circuit containing the diode. Equivalent circuits may also be used as device *models* for computer analysis.

forward V drop
negligible series R

(a) Basic dc equivalent circuit

In Ex. 2-3, a forward-biased diode is assumed to have a constant forward voltage drop (V_F) and negligible series resistance. In this case the diode equivalent circuit is assumed to be a voltage cell with a voltage V_F (see Fig. 2-11a). This simple dc equivalent circuit is quite suitable for a great many diode applications.

diode dynamic R



(b) Complete dc equivalent circuit

Figure 2-11 DC equivalent circuits for a junction diode.

A more accurate equivalent circuit includes the diode dynamic resistance (r_d) in series with the voltage cell, as shown in Fig. 2-11b. This takes account of the small variations in V_F that occur with change in forward current. An ideal diode is also included to show that current flows only in one direction. The equivalent circuit without r_d assumes that the diode has the approximate characteristics illustrated in Fig. 2-8b or c. With r_d included, the equivalent circuit represents a diode with the type of piecewise linear characteristic shown in Fig. 2-10. Consequently, the circuit in Fig. 2-11b is termed the *piecewise linear equivalent circuit*.

Example 2-5

Calculate I_F for the diode circuit in Fig. 2-12a assuming that the diode has $V_F = 0.7\ \mathrm{V}$ and $r_d = 0$. Then recalculate the current taking $r_d = 0.25\ \Omega$.

Solution

Substituting V_F as the diode equivalent circuit (Fig. 2-12b),

$$I_F = \frac{E - V_F}{R_1} = \frac{1.5\ \text{V} - 0.7\ \text{V}}{10\ \Omega}$$

$$= 80\ \text{mA}$$

Substituting V_F and r_d as the diode equivalent circuit (Fig. 2-12c),

$$I_F = \frac{E - V_F}{R_1 + r_d} = \frac{1.5\ \text{V} - 0.7\ \text{V}}{10\ \Omega + 0.25\ \Omega}$$

$$= 78\ \text{mA}$$

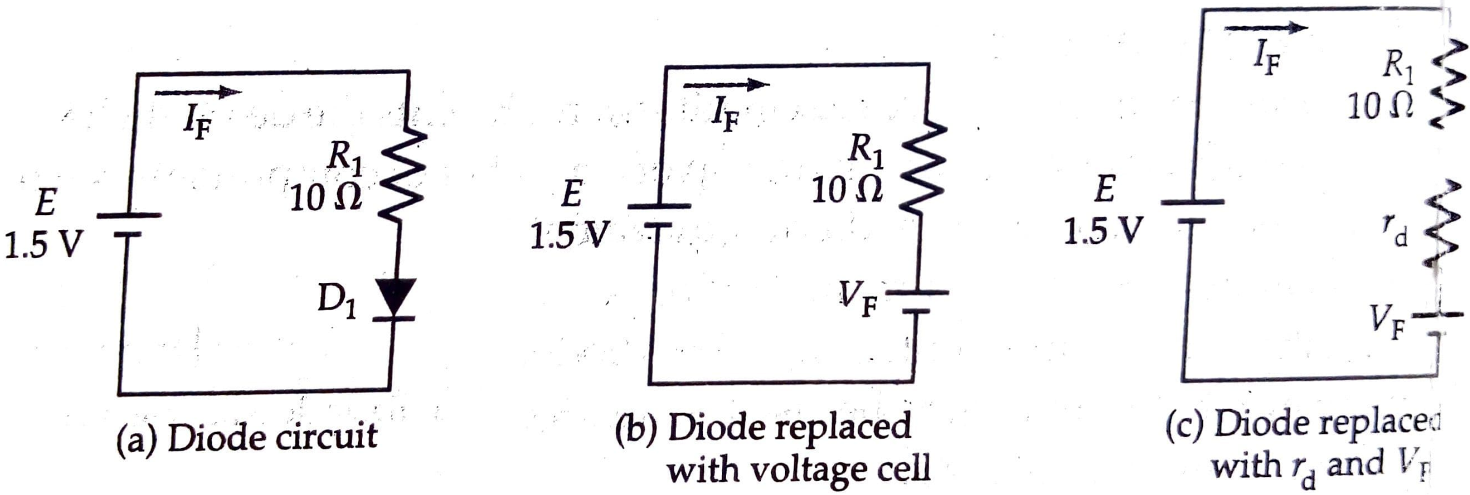
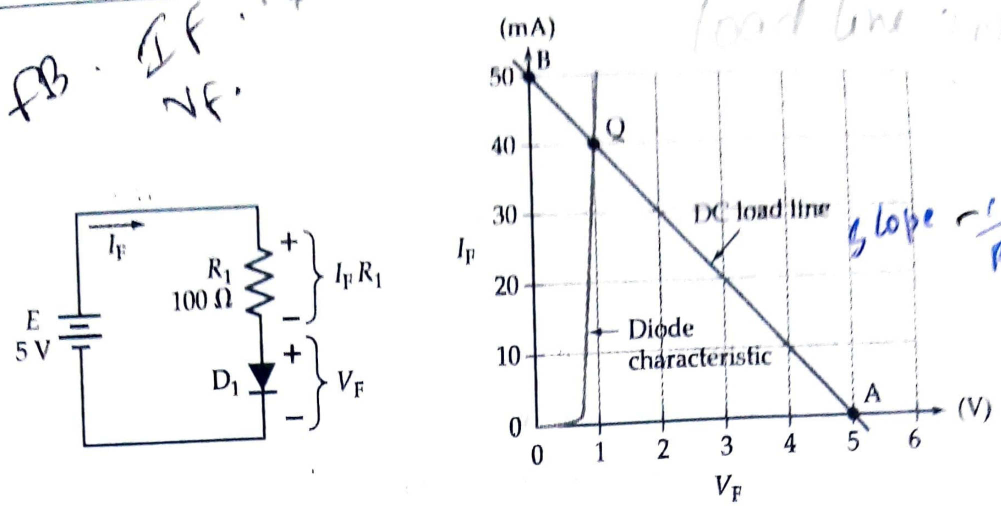


Figure 2-12 Diode circuits for Ex. 2-5.

2-4 DC LOAD LINE ANALYSIS

DC Load Line

Figure 2-13a shows a diode in series with a 100 Ω resistor (R_1) and a supply voltage (E). The polarity of E is such that the diode is forward-biased, so that there is a diode forward current (I_F). As already discussed, the circuit current can be determined approximately by assuming a constant diode forward voltage drop (V_F). When the precise levels of the diode current and voltage must be calculated, *graphical analysis* (also termed *dc load line analysis*) is employed.



(a) Diode-resistor series circuit

(b) Plotting the dc load line on the diode characteristics

Figure 2-13 Drawing a dc load line on the diode characteristic.

For graphical analysis, a dc load line is drawn on the diode forward characteristics (Fig. 2-13b). This is a straight line that illustrates all dc conditions that could exist within the circuit. Because the load line is always straight, it can be constructed by plotting any two corresponding current and voltage points and then drawing a straight line through them. To determine two points on the load line, an equation relating voltage, current, and resistance is first derived for the circuit. From Fig. 2-13a,

$$E = (I_F R_1) + V_F \tag{2-3}$$

Any two convenient levels of I_F can be substituted into Eq. 2-3 to calculate corresponding V_F levels, or vice versa. As demonstrated in Ex. 2-6, it is convenient to calculate V_F when $I_F = 0$, and to determine I_F when $V_F = 0$.

Example 2-6

Draw the dc load line for the circuit in Fig. 2-13a on the diode forward characteristic given in Fig. 2-13b.

Solution

Substitute $I_F = 0$ into Eq. 2-3,

$$E = (I_F R_1) + V_F = 0 + V_F$$

or

$$V_F = E = 5\text{ V}$$

Plot point A on the diode characteristic at

$$I_F = 0 \text{ and } V_F = 5\text{ V}$$

Now substitute $V_F = 0$ into Eq. 2-3,

$$E = (I_F R_1) + 0$$

giving

$$I_F = \frac{E}{R_1} = \frac{5\ \text{V}}{100\ \Omega}$$

$$= 50\ \text{mA}$$

Plot point B on the diode characteristic at

$$I_F = 50\ \text{mA and}\ V_F = 0$$

Draw the dc load line through points A and B.

Q-Point

The relationship between the diode forward voltage and current in the circuit in Fig. 2-13a is defined by the device characteristic. Consequently, there is only one point on the dc load line where the diode voltage and current are compatible with the circuit conditions. That is *point Q*, termed the *quiescent point* or *dc bias point*, where the load line intersects the characteristic. This may be checked by substituting the levels of I_F and V_F at point Q into Eq. 2-3. From the Q point on Fig. 2-13b, $I_F = 40$ mA and $V_F = 1$ V. Equation 2-3 states that $E = (I_F R_1) + V_F$. Therefore,

$$E = (40\ \text{mA} \times 100\ \Omega) + 1\ \text{V}$$

$$= 5\ \text{V}$$

So, with $E = 5$ V and $R_1 = 100\ \Omega$, the only levels of I_F and V_F that can satisfy Eq. 2-3 on the diode characteristics in Fig. 2-13b are 40 mA and 1 V.

Note that, although 0 and 5 V were used for V_F when the dc load line was drawn in Ex. 2-6, no functioning semiconductor diode would have a 5 V forward voltage drop. This is simply a convenient theoretical level for plotting the dc load line.

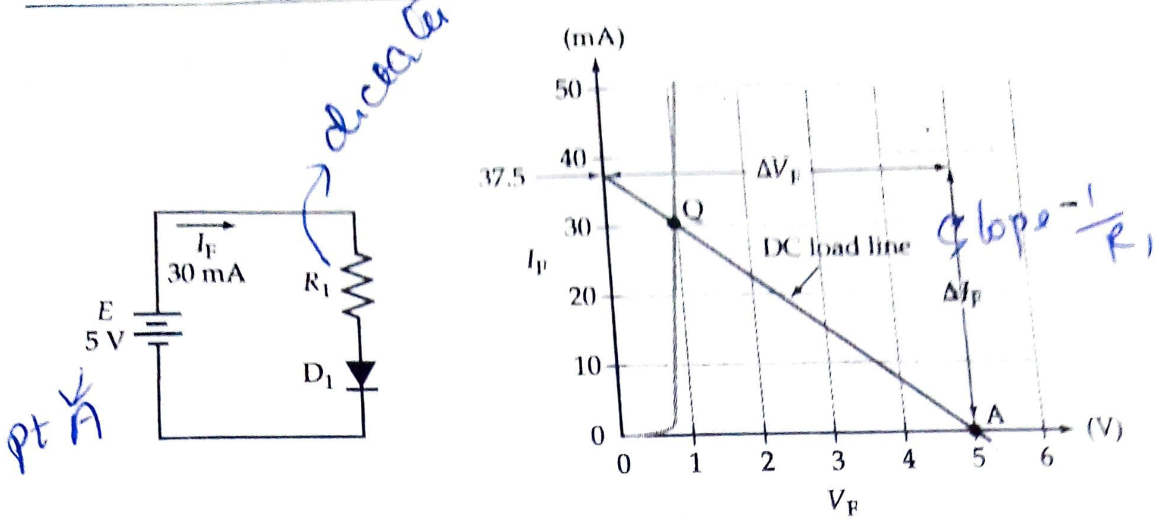
Calculating Load Resistance and Supply Voltage

In a diode series circuit (see Fig. 2-14a), resistor R_1 dictates the slope of the dc load line, and supply voltage E determines point A on the load line. So the circuit conditions can be altered by changing either R_1 or E.

When designing a diode circuit, it may be necessary to use a given supply voltage and set up a specified forward current. In this case, points A and Q are first plotted and the load line is drawn. Resistor R_1 is then calculated from the slope of the load line. The problem could also occur in another way. For example, R_1 and the required I_F are known, and the supply voltage is to be

A, Q plott, line draw, R_1 - found from slope

R_1 & I_F known, E need to be found



(a) Diode-resistor circuit

(b) Resistor determination

Figure 2-14 Determination of the required circuit series resistance R_1 from the slope of the dc load line.

determined. This problem is solved by plotting point Q and drawing the load line with slope $1/R_1$. The supply voltage is then read at point A.

Example 2-7

Using the device characteristics in Fig. 2-14b, determine the required load resistance for the circuit in Fig. 2-14a to give $I_F = 30$ mA.

Solution

From Eq. 2-3, $$V_F = E - (I_F R_1)$$

Substituting $I_F = 0$, $$V_F = E - 0 = 5\ \text{V}$$

Plot point A on the diode characteristic in Fig. 2-14b at

$$I_F = 0 \text{ and } V_F = 5\ \text{V}$$

Now plot point Q in Fig. 2-14b at

$$I_F = 30\ \text{mA}$$

$V_F = 5-(30mA$

Draw the dc load line through points A and Q. From the load line,

$$R_1 = \frac{\Delta V_F}{\Delta I_F} = \frac{5\ \text{V}}{37.5\ \text{mA}}$$

$$= 133\ \Omega$$

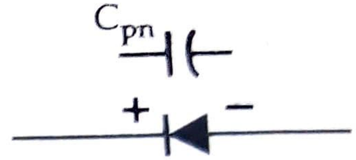
2-6 DIODE AC MODELS

Junction Capacitances

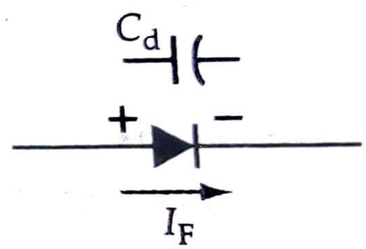
The depletion region of a *pn*-junction (see Section 1-6) is a layer depleted of charge carriers situated between two blocks of low-resistance material. Since this is also the description of a capacitor, the junction depletion region clearly has a capacitance. The *depletion layer capacitance* (C_{pn}) (also known as the *transition capacitance*) may be calculated from the equation for a parallel-plate capacitor if the junction dimensions are known. Typically, C_{pn} is 4 pF for a low-current diode.

dep cap
transition
Cap
pn = 4pF

The depletion layer capacitance is essentially the capacitance of a reverse-biased *pn*-junction (Fig. 2-18a). Consider the forward-biased junction in Fig. 2-18b. If the applied



(a) A depletion layer capacitance occurs at a reverse-biased diode



(b) A diffusion capacitance is present at a forward-biased diode

Figure 2-18 The capacitance of a diode depends upon the polarity of the applied voltage and on the current level. The diffusion capacitance is much larger than the depletion layer capacitance.

voltage is suddenly reversed, forward current I_F ceases immediately, leaving some majority charge carriers in the depletion region. These charge carriers must flow back out of the depletion region, which is widened when the junction is reverse-biased. The result is that, when a forward-biased junction is suddenly reversed, there is a reverse current, which is large at first and which slowly decreases to the level of the reverse saturation current. The effect may be likened to the discharge of a capacitor, and so it is represented by a capacitance known as the *diffusion capacitance* (C_d) (also termed the *storage capacitance*).

The equation for the diffusion capacitance is

$$C_d \approx \frac{\tau I_F}{V_F} \tag{2-8}$$

where I_F and V_F are the forward current and voltage, and τ is the *transist time* of charge carriers. The transit time is dependent on the doping density of the semiconductor material, and on whether the *p*-side or the *n*-side of the junction is most heavily doped. It is to be expected that C_d would be directly proportional to I_F since the quantity of charge carriers in the depletion region is dependent on the forward current level.

Example 2-11

Calculate the diffusion capacitance for a silicon diode with a 10 mA forward current if the charge carrier transit time is 70 ns.

Solution

Eq. 2-8:

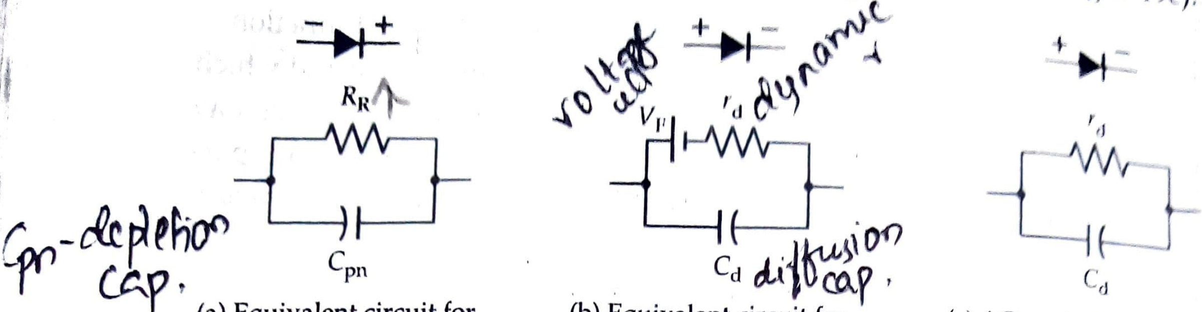
$$C_d \approx \frac{\tau I_F}{V_F} \approx \frac{70\text{ ns} \times 10\text{ mA}}{0.7\text{ V}}$$

$$\approx 1\text{ nF}$$

AC Equivalent Circuits (Reverse-Biased and Forward-Biased)

A reverse-biased diode can be simply represented by the high reverse resistance R_R in parallel with the depletion layer capacitance C_{pn} (see Fig. 2-19a). The equivalent circuit (or model) for a forward-biased diode consists of the dynamic resistance r_d in series with a voltage cell representing V_F, as discussed in Section 2-3. To allow for the effect of the diffusion capacitance, C_d is included in parallel to give the complete equivalent circuit shown in Fig. 2-19b.

The complete equivalent circuit for the forward-biased diode may be modified into an *ac equivalent circuit*, which can be used for diodes that are maintained in a forward-biased condition while subjected to small variations in I_F and V_F. The ac equivalent circuit is created simply by removing the voltage cell representing V_F from the complete equivalent circuit (Fig. 2-19c).



(a) Equivalent circuit for a reverse-biased diode

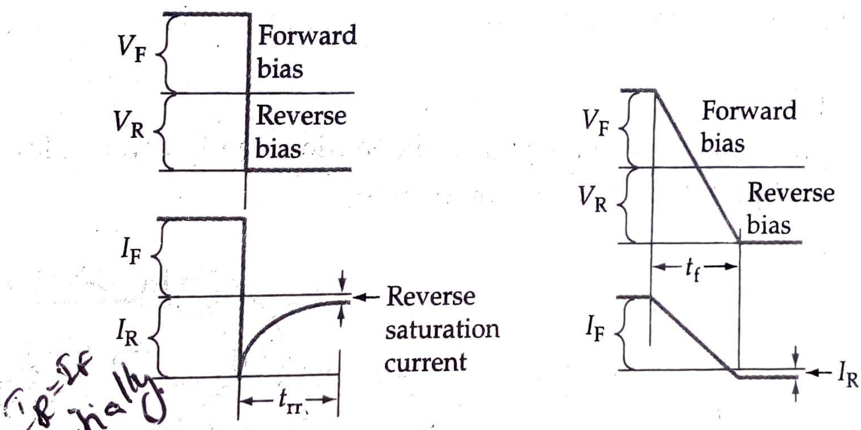
(b) Equivalent circuit for a forward-biased diode

(c) AC equivalent circuit for a forward-biased diode

Figure 2-19 Equivalent circuits (or models) for reverse-biased and forward-biased diodes.

Reverse Recovery Time

In many applications, diodes must switch rapidly between forward and reverse bias. Most diodes switch very quickly into the forward-biased condition; however, there is a longer *turnoff* time owing to the junction diffusion capacitance.



(a) Effect of instantaneous reverse bias

(b) Effect of $t_f >> t_{rr}$

Figure 2-20 The minimum on-off switching time of a diode is limited by the reverse recovery time (t_{rr}). The reverse saturation current can be minimized by using a pulse with $t_f >> t_{rr}$.

Figure 2-20 illustrates the effect of a voltage pulse on the diode forward current. When the pulse switches from positive to negative, the diode conducts in reverse instead of switching off sharply (see Fig. 2-20a). The reverse current (I_R) initially equals the forward current (I_F); then it gradually decreases toward zero. The high level of reverse current occurs because at the instant of reverse bias there are charge carriers crossing the junction depletion region, and these must be removed. (This is the same effect that produces diffusion capacitance.) The *reverse recovery time* (t_{rr}) is the time required for the current to decrease to the reverse saturation current level.

Typical values of t_{rr} for switching diodes range from 4 ns to 50 ns. The diode reverse current can be kept to a minimum if the *fall time* (t_f) of the applied voltage pulse is much larger than the diode reverse recovery time. This is illustrated in Fig. 2-20b. Typically

$$t_{f(min)} = 10\, t_{rr} \tag{2-9}$$

Example 2-12

Calculate the minimum fall times for voltage pulses applied to a circuit using 1N915 and 1N917 diodes to keep the diode reverse current to a minimum.

Solution

From diode data sheets,

$$t_{rr} = 10 \text{ ns for the 1N915} \quad \text{and} \quad t_{rr} = 3 \text{ ns for the 1N917}$$

For the 1N915:

Eq. 2-9:
$$t_{f(min)} = 10\, t_{rr} = 10 \times 10 \text{ ns}$$
$$= 100 \text{ ns}$$

For the 1N917:

Eq. 2-9:
$$t_{f(min)} = 10\, t_{rr} = 10 \times 3 \text{ ns}$$
$$= 30 \text{ ns}$$

Practice Problems

2-6.1 Determine the maximum reverse recovery time for satisfactory operation of a diode with an applied voltage pulse which has a 0.5 μs fall time.

2-6.2 Estimate a suitable minimum fall time for a pulse which switches a diode from *on* to *off* if the reverse recovery time of the diode is 15 ns.

2-6.3 Determine the charge carrier transit time for a silicon diode which has a capacitance of 11 nF when the forward current is $I_F = 50$ mA.

2-7 DIODE SPECIFICATIONS

Diode Data Sheets

To select a suitable diode for a particular application, the *data sheets*, or *specifications*, provided by device manufacturers must be consulted. Portions of typical diode data sheets are shown in Fig. 2-21 and as data sheets 1 to 3 in Appendix A.