Lecture-8

Large, Small Signal Model and Switching Characteristics of Diode

Large Signal Model of the Diode: It is convenient to represent the diode by a combination of ideal, linear circuit elements called an equivalent circuit or circuit model. As the diode is used with other circuit elements or devices, the model allows us to evaluate the currents and voltages in the network using standard circuit analysis methods. The ideal diode (Fig.1) is a binary device in the sense that it exists in only one of two possible states; that is, the diode is either ON or OFF at a given time. Consider a real diode such as that whose characteristics shown in Fig.2. If the applied voltage across this diode exceeds the cut-in voltage V_γ, with the anode A (the p side) more positive than the cathode K (the n side), the diode is forward-biased and is in the ON state. Thee OFF state exists when the applied voltage is less than V_γ and, in effect, reverse-biases the diode. As shown in Fig.2(a), the two line segments approximate the forward characteristic of the diode. The piecewise representation is modeled by a voltage source V_γ in series with a resistance R_f (usually 5 to 50 Ω for silicon diodes) as depicted in Fig.2(b). This piecewise linear characteristic has value because for $v_D < V_\gamma$, the forward current is sufficiently small that it can be neglected. Furthermore, the diode voltage drop is generally small in comparison with the applied voltages in the circuit so that the difference between the straight line and the actual characteristic introduces negligible error. In effect, the ON state can be regarded as an ideal diode in series with a battery V_γ and a resistor R_f.

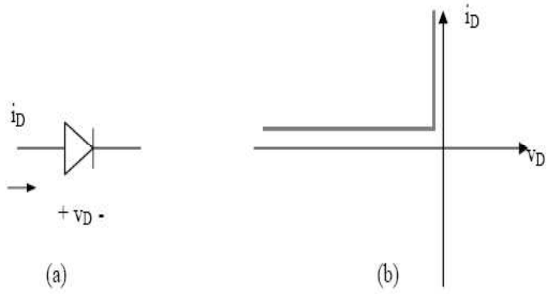

Figure 1: (a)Circuit Symbol; (b) volt-ampere characteristics of an ideal diode

For the OFF state, the diode characteristic is approximated by the straight line passing through the origin depicted in Fig.3(a), the slope of which is $1/R_r$. This representation gives rise to the equivalent circuit in Fig.3(b). As R_r is generally several hundreds of kilo-ohms or more, we can often assume that it is infinite and consider

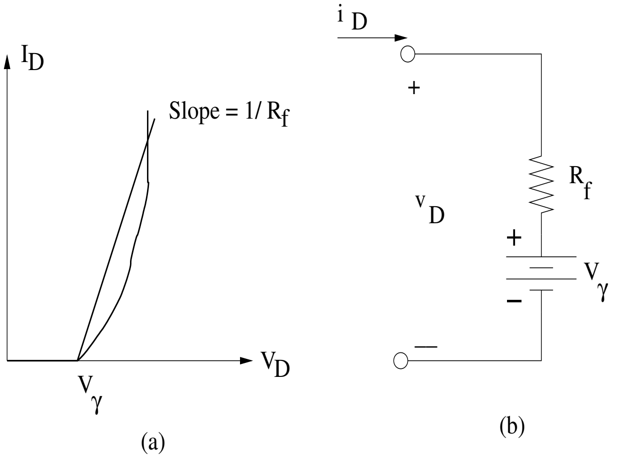

Figure 2: (a) Piecewise linear diode forward characteristics; (b) diode model for forward bias

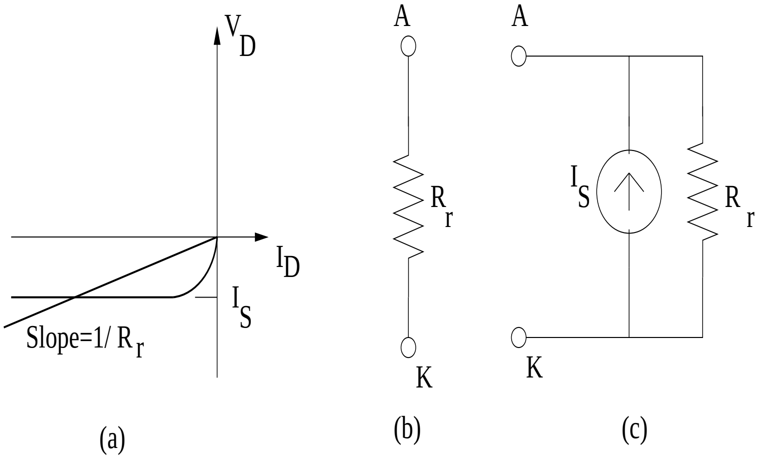

Figure 3: (a) Piecewise linear diode reverse characteristics; (b) diode model based on piecewise linear representation; (c) model to include surface leakage

the reverse-biased diode as an open circuit. Where higher degrees of accuracy are required, the model shown in Fig.3(c) is useful. The current source I_S is used to indicate the constant reverse saturation current. The resistance R_r in Fig.3(c) may also take into account the increase in reverse current with increasing reverse voltage caused by surface leakage.

Small-signal diode model: The circuits described in the previous section utilized the ON-OFF behavior of diodes. In these applications the applied signal (usually time varying) is large in comparison to the bias level (the constant reference voltage) and the models in Figs.2 and 3 are used to describe the diode. We now consider the situation where the signal amplitude is small compared to the bias. It is convenient to use small-signal or incremental equivalent circuits to represent the diode in order to enable us to relate the response component due to the applied (excitation) signal $v_S(t)$. The circuit in Fig.4(a) is useful in developing the small-signal models. In the circuit of Fig.4(a), $V_m < V_{AA}$, so that the diode remains forward biased at all times. The instantaneous value of the voltage $v(t)$ applied to the diode-resistance combination is

$$v(t) = V_{AA} + V_m \sin \omega t \ V \tag{1}$$

At each instant of time, we can draw a load line (Fig.4(b)). Maximum and minimum values of $v(t)$ are $V_{AA} + V_m$ and $V_{AA} - V_m$, respectively, and, for $\omega t = n\pi$ where n is an integer, $v = V_{AA}$. As shown in Fig. 4(c), the current i_D is composed of a sinusoidal component superimposed on the quiescent level I_{DQ} and is expressed as

$$i_D = I_{DQ} + i_d(t) = I_{DQ} + I_d \sin \omega t \ A \tag{2}$$

In Eqn. (2), i_D is the instantaneous value of diode current and I_{DQ} the DC component of i_D and i_d is the time-varying component of i_D whose peak value is given by I_d. The form of the current expressed in Eqn.(2) results from the fact that the diode characteristic between Q_1 and Q_2 can be approximated by a straight line whose slope is that of the diode volt-ampere relation evaluated at Q. In this region, therefore, the diode behaves linearly and, in effect, superposition applies. That is, the quiescent (DC) value I_{DQ} is established by the constant bias supply V_{AA} and the sinusoidal component $i_d(t)$ is produced by the excitation $v_s(t)$. The time-varying components of the voltages and currents in the circuit in Fig. 4(a) can be determined analytically (instead of graphically as in Fig. 4(c)) by applying Kirchhoffs laws to the small-signal equivalent circuit shown in Fig.5. Here the diode is replaced by its incremental resistance $r_d \equiv 1/g_d$, where the incremental conductance g_d is given by

$$g_d \equiv \left. \frac{di_D}{dv_D} \right|_Q \quad \mho \tag{3}$$

Note that g_d is simply the slope of the diode characteristic evaluated at the operating point Q, and consequently the value of r_d is a function of the quiescent current. To make use of the circuit in Fig.3-9, we must first establish the quiescent values of diode current and voltage. For a junction diode, Eqn.(3) becomes, using Eqn.(25) of LN-4

$$g_d = \frac{I_S e^{V_{DQ}/\eta V_T}}{\eta V_T} = \frac{I_{DQ} + I_S}{\eta V_T}\ \mho \tag{4}$$

Most often, $I_{DQ} \gg I_S$, so that Eqn.(4) reduces to,

$$r_d = \frac{1}{g_d} \approx \frac{\eta V_T}{I_{DQ}}\ \Omega \tag{5}$$

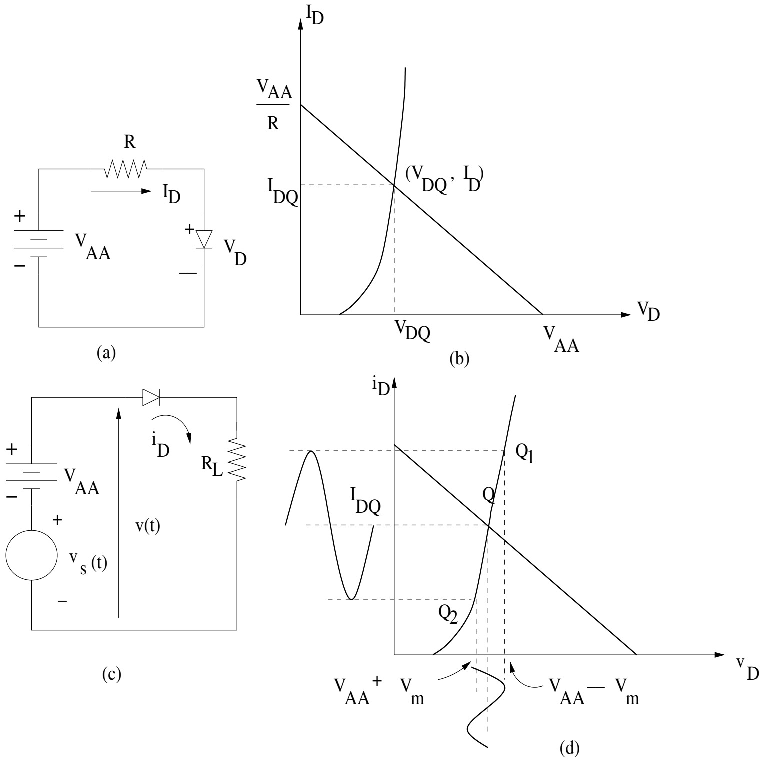

Figure 4: (a) Diode Circuit ; (b) diode characteristics and the load line for the circuit; (c) Diode circuit with constant and sinusoidal voltage excitation; (d) variation in load line and input and output waveforms for current in part (c)

Switching Charateristics of Diode: The transient response of a diode driven from an ON to an OFF state, or in the opposite direction, signifies that an interval of time elapses before the diode reaches its new steady state. Because it represents

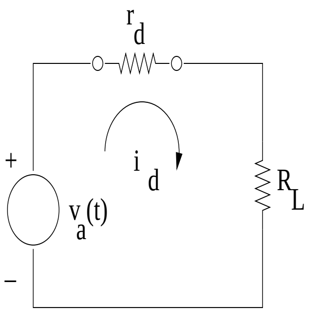

Figure 5: Small-Signal equivalent circuit of the Fig.4(a)

an important practical limitation, the reverse recovery, that is,switching from ON to OFF, is treated in the following paragraphs.

The sequence of events which accompanies the reverse-biasing of a conducting diode is depicted in Fig.6. We consider that the step input voltages v_i in Fig. 6(b) is applied to the diode-resistor circuit in Fig. 6(a) and that for a long time prior to $t = 0$ the voltage $v_i = V_F$ forward-biases the diode. At $t = 0$, the applied voltage abruptly changes to V_R and remains at this level for $t > 0$. If we assume that R_L and V_F are much large than R_f and V_γ, respectively, the circuit current $i_D \approx V_F/R_L$. This value is indicated for $t \leq 0$ in Fig.1(c). The forward bias causes a large number of carriers to diffuse across the junction so that the excess minority-carrier density is high. Under reverse-biased conditions the excess minority carriers in the vicinity of the junction is virtually zero. Consequently, sudden reversal of the voltage cannot be accompanied by a change in the sate of the diode until the number of excess minority carriers is reduced to zero. That is, these carriers must be swept back across the junction to the side from which they originated. This charge motion produces a current in the reverse direction. The period of time during which the excess minority carriers decrease to zero, between $t = 0$ and $t = t_1$, is called the *storage time* t_s. During this time interval the diode conducts easily; the current, determined by the applied voltage and external load resistance, is V_R/R_L. The voltage drop across the diode across the diode is decreased slightly because of the change in current in the ohmic resistance of the diode but does not reverse (Fig.6(d)). At $t = t_1 = t_s$ the excess minority-carrier density becomes zero. Subsequent to this time, the diode voltage begins to reverse toward V_R and the magnitude of the current decreases toward I_S or I_0 (i.e reverse saturation current).

The time which elapses between t_1 and the time when the diode has nominally recovered is called the *transition time* t_1. This recovery interval will be completed when the minority carriers which are at some distance from the junction have diffused to the junction and crossed it and when, in addition, the junction transition capacitance across the reverse biased junction has charged through R_L to the voltage V_R. Manufacturers normally specify the reverse recovery time t_{rr} of a diode in a typical operating condition in terms of the current waveform in Fig. 6(c). The time t_{rr} is the interval from the current reversal at $t = 0$ until the diode has recovered to a specified extent in terms of either the diode current or the diode resistance. If the specified value of R_L is larger than several hundred ohms, ordinarily the manufacturers will specify the capacitance C_L shunting R_L in the measuring circuit which is used to determine t_{rr}. Commercial switching-type diodes are available with times t_{rr} in the range from less than 1 nanosecond (ns) up to as high as 1 microsecond (μs) in diodes intended for switching large currents. The forward recovery time t_{rf} is the time required for the diode voltage to change from 10 to 90 percent of its final value when the diode is switched from OFF to ON. Since $t_{rf} \ll t_{rr}$, it is usual practice to neglect t_{rf}.

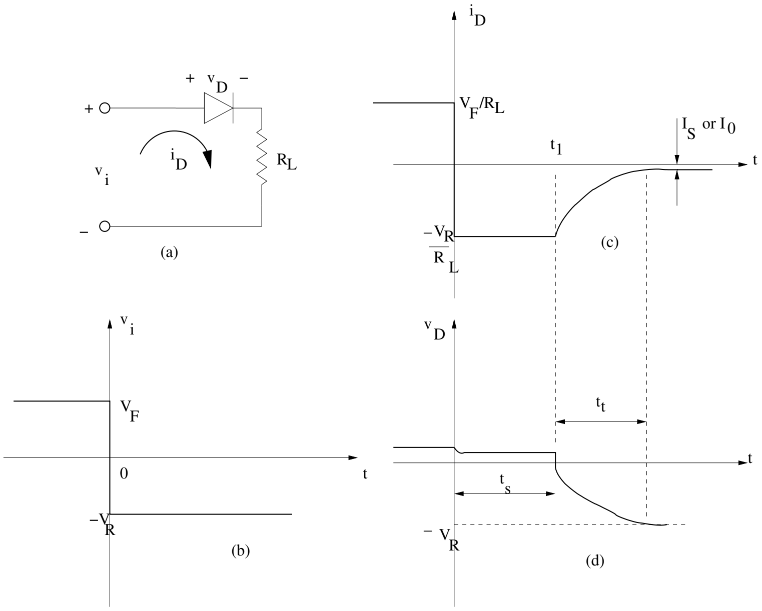

Figure 6: (a) Diode-resistor circuit; (b) input waveform applied to circuit in part a showing abrupt change from forward to reverse bias; (c) current and (d) diode voltage waveforms displaying storage and transition times.