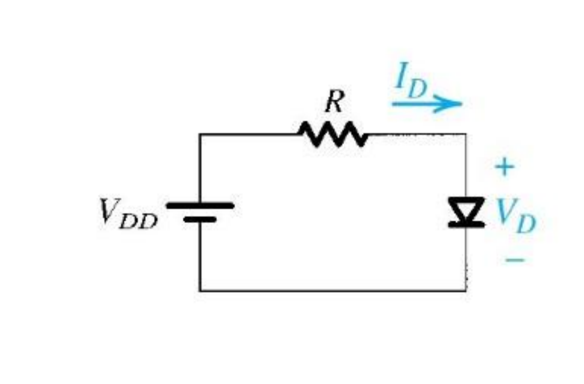
ENGR 305

Modeling the diode

September 11, 2025

Modeling the diode

- We can begin analyzing circuits using a forward-conducting diode.
- The circuit consists of a dc source V_{DD}, a resistor R, and a diode.
- So far we have two models with which to analyze the circuit
  - The ideal diode model
  - The exponential model

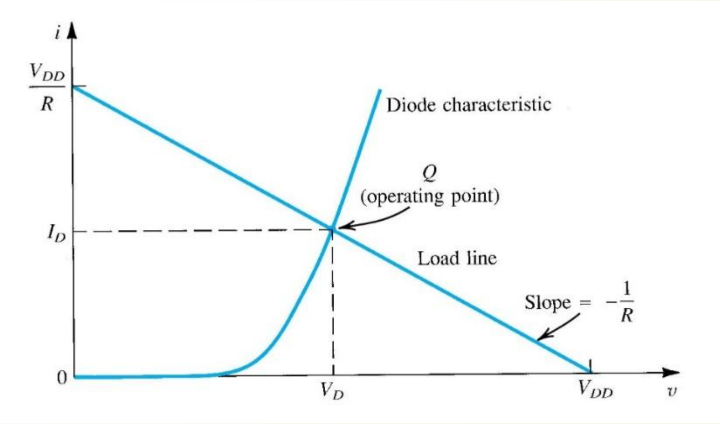


Modeling the diode – exponential model

- Because this model is nonlinear, it is more difficult to use.
- Assuming that V_{DD} is much greater than 0.5 V, the diode current will be much greater than I_S and we can represent the diode current as
  - $I_D = I_S e^{V_D/V_T}$
- The other equation for the circuit is found by writing a Kirchoff loop equation
  - $I_D = \frac{V_{DD}-V_D}{R}$
- If the value of I_S is known, the two equations represent two equations in the two unknowns, I_D and V_D.
- The solution can be found using either graphical analysis or iterative analysis.

Graphical analysis – exponential model

- Graphical analysis is performed by plotting the two equations on the *i-v* plane.
- The solution is found at the intersection of the two graphs.
  - The straight line is known as the **load line.**
  - The load line intersects the diode curve at point Q, which represents the **operating point** of the circuit, given by I_D and V_D.

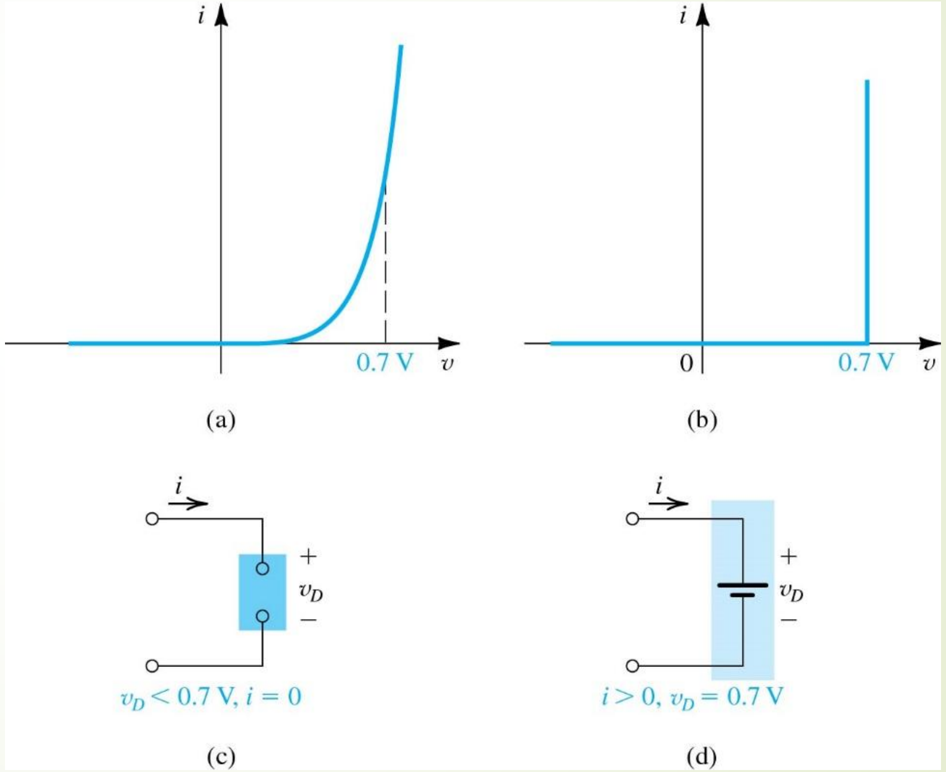


Constant-voltage-drop model

- We often need rapid and simple circuit analysis.
- The simplest and most widely used diode model is the constant-voltage drop model.
  - It assumes that the voltage across the diode is a **constant 0.7 V**.
  - The actual value is in the range of 0.6-0.8 V.
  - With a forward voltage below 0.7 V, it assumes zero diode current.

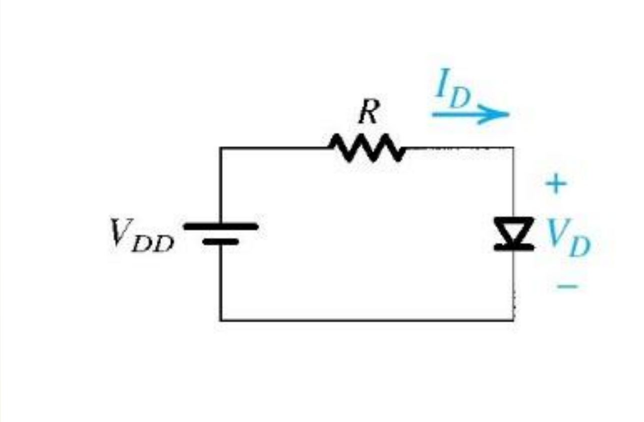
Diode constant-voltage-drop model

The figure shows the development of the diode constant-voltage-drop model. (a) the exponential characteristic; (b) approximating the exponential characteristic by a piecewise-linear one; (c) the resulting model of the diode with reverse bias or $v_D < 0.7V$; (d) model of the forward-conducting diode.



The ideal-diode model

- For applications that involve voltages much greater than the diode voltage drop (0.6 V-0.8 V), we may neglect the diode voltage drop altogether in the calculation.
- Considering the circuit with $V_{DD} = 5\ V$ and $R = 1\ k\Omega$
- Using the ideal-diode model, we obtain
  - $V_D = 0\ V$
  - $I_D = \frac{5-0}{1} = 5\ mA$
- The ideal-diode model is usually used
  - To determine which diodes are on and off

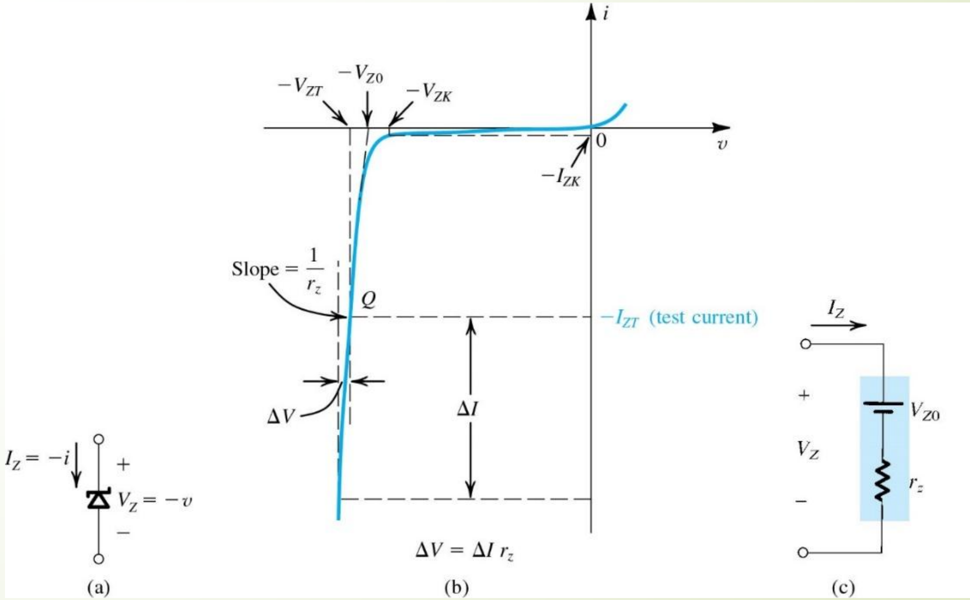


Reverse breakdown region

- The *i-v* curve is very steep in the breakdown region.
  - This suggests that we can use diodes operating in the breakdown region for amplification and in circuits whose purpose is to maintain nearly constant dc voltages.
  - There are two reverse breakdown mechanisms: **avalanche and zener**
- **Avalanche breakdown**
  - Avalanche breakdown is typically observed with $V_{BR} \geq 10\ V$
  - It is the more common form of reverse breakdown for diodes to withstand a high reverse voltage without appreciable current.
  - We need to limit the reverse current; otherwise, overheating can cause permanent damage to the diode.

Zener breakdown and the zener diode

- Zener diodes maintain a nearly constant reverse voltage drop, V_Z, over a wide range of reverse currents.
- Part (a) of the figure shows the circuit symbol of the zener diode indicating the polarity of V_Z and current flow in normal applications.



Zener breakdown and the zener diode

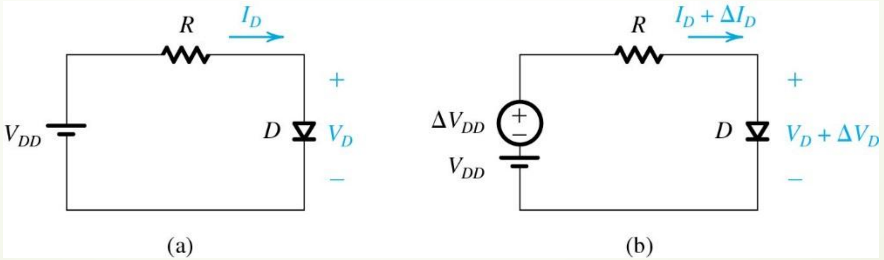
- Part (b) of the figure shows some details of the diode *i-v* characteristic.
- The manufacturer often specifies several key parameters:
  - The reverse voltage V_{ZT} at a test current I_{ZT} corresponding to the operating point Q. Typical values for V_{ZT} are below 10 V, although higher voltages are possible.
  - The "knee" current I_{ZK}, corresponding to the reverse current at the onset of zener operation.
  - The maximum power the device can safely dissipate. For example, a 0.5-W, 6.8-V zener diode can operate safely at currents up to a maximum of about 70 mA.
  - The **temperature coefficient** (TC) of the zener voltage V_Z, commonly known as its **temco** and expressed in $mV/°C$

Zener diode

- The incremental resistance of the zener, r_z, will also be specified.
- It relates changes in current, ΔI, to the resulting change in reverse voltage, $\Delta V = r_z \Delta I$
- Lower values of r_z indicate a steeper *i*-v curve and, hence, a more constant reverse voltage.
- V_{Z0} denotes the point at which the straight line of slope ${}^{1}/_{r_z}$ intersects the voltage axis in the figure.
- The equivalent circuit model is analytically described by
  - $V_Z = V_{Z0} + r_z I_Z$

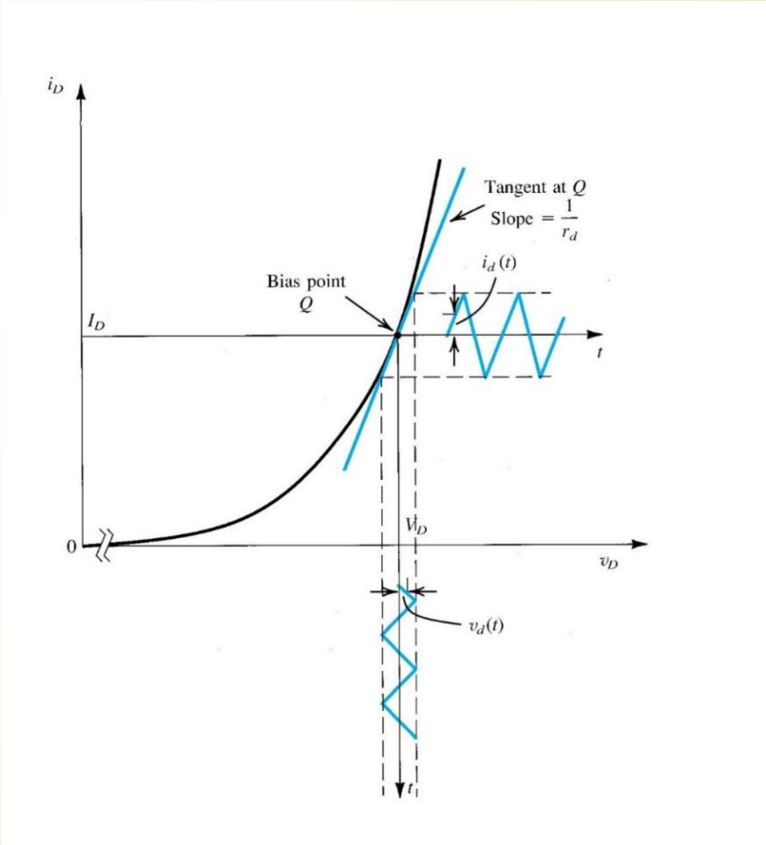
Small-signal model

- We now consider a technique that preserves the benefits of linear circuit analysis but provides more accuracy than piecewise-linear models.
  - The circuit voltages and currents must stay within a narrow range.
- In the figure we have a circuit where a dc voltage V_{DD} establishes a dc current I_D through a series combination of a resistance R and a diode D.
- Then the voltage V_{DD} undergoes a small change Δ V_{DD} as shown.



Small-signal model

We want to develop a “small-signal” model to determine the values of incremental changes in the voltage and current in the circuit.



Small-signal model

- We express the voltage across the diode as the sum of the dc voltage V_D and the time-varying signal $v_d(t)$
  - $v_D(t) = V_D + v_d(t)$
- The total instantaneous diode current $i_D(t)$ will be
  - $i_D(t) = I_S e^{v_D/V_T}$
- Substituting for v_D gives
  - $i_D(t) = I_S e^{(V_D+v_d)/V_T} = I_S e^{V_D/V_T} e^{v_d/V_T}$
- In the absence of a signal voltage, the diode voltage equals V_D and
  - $I_D = I_S e^{V_D/V_T}$
  - Then $i_D(t) = I_D e^{v_d/V_T}$

Small-signal model

- If the signal $v_d(t)$ is kept sufficiently small, such that $\frac{v_d}{V_T} \ll 1$
  - We can then expand the exponential in a series and truncate the series after two terms
  - The resulting expression is $i_D(t) \cong I_D\left(1 + \frac{v_d}{V_T}\right)$
- This result is the **small-signal approximation**, and it is valid when the variation in the diode voltage, v_d, is smaller than 5 mV.
- Superimposed on the dc current I_D is a signal current component that is proportional to the signal voltage v_d.
  - $i_D = I_D + i_d$

Small-signal model

- Using the small-signal approximation for the voltage, this gives
  - $i_d = \frac{I_D}{V_T} v_d$ and then $v_d = \frac{V_T}{I_D} i_d$
- The quantity that relates the signal current to the signal voltage is the **diode small-signal resistance**
  - $r_d = \frac{V_T}{I_D}$
- Looking back at the figure we see the diode operating at a dc bias point Q characterized by the dc voltage V_D and the corresponding dc current I_D.
- Superimposed on the dc quantities we have (in this case) a triangular waveform $v_d(t)$

Small-signal model

- Using the small-signal approximation is equivalent to assuming that
  - *The signal amplitude is sufficiently small such that the excursion along the i-v curve is limited to a short almost-linear segment.*
- The slope of this segment is equal to the slope of the tangent to the i-v curve at the operating point Q.
- The slope of the *i*-v curve at $i = I_D$is equal to I_D/V_T ,which is ${}^{1}/_{r_d}$
  - This is the **small-signal conductance**
  - $r_d = \frac{1}{small-signal\ conductance} = {}^{1}/_{\left[\frac{\partial i_D}{\partial v_D}\right]_{i_D=I_D}}$

Small-signal model

- We conclude that superimposed on the quantities V_D and I_D that define the dc bias point, or **quiescent point,** of the diode will be the small-signal quantities $v_d(t)$ and $i_d(t)$.
- These are related by the diode small-signal resistance r_d evaluated at the bias point.
- The small-signal analysis can be performed separately from the dc bias analysis.