CHAPTER 4

Diodes

(non-linear devices)
Diode structure

(a) P-type material | N-type material
Depletion region

(b) Anode | Cathode
Schematic symbol
Stripe marks cathode

(c) Real component appearance
Figure 4.1 The ideal diode: (a) diode circuit symbol; (b) $i-v$ characteristic; (c) equivalent circuit in the reverse direction; (d) equivalent circuit in the forward direction.
Figure 4.2 The two modes of operation of ideal diodes and the use of an external circuit to limit (a) the **forward current** and (b) the **reverse voltage**.
Simple diode application: rectifier

\[ T = \frac{1}{f} \]

- \( T \) = period (second, 16.7ms)
- \( f \) = frequency (Hertz, 60Hz)

Figure 4.3 (a) Rectifier circuit. (b) Input waveform.
Simple diode application: the rectifier

1. (c) Equivalent circuit when $v_I \geq 0$. (d) Equivalent circuit when $v_I \leq 0$. (e) Output waveform.
Example 4.1.

- The diode conducts when $V_s$ exceeds 12V
- The diode stops conducting when $V_s$ falls below 12V
- The current $i_D$ flows in the conduction angle $2\theta$
- $12V = 24V \times \cos(\theta)$ then $\theta = 60^\circ$ or conduction angle $2\theta = 120^\circ$
- Maximum current (peak current) $I = (24-12)/100 = 120mA$
Simple diode application: the diode logic gates

Figure 4.5 Diode logic gates: (a) OR gate; (b) AND gate (in a positive-logic system).
Example 4.2.
Exercise 4.4

(a) 

(b) 

(c) 

(d) 

(e) 

(f)
Terminal Characteristics of Junction Diodes

\[ i_D = I_S \left( e^{\frac{v}{VT}} - 1 \right) \quad \rightarrow \quad v_D = V_T \ln \frac{i}{I_S} \]

Thermal voltage: \( V_T = \frac{kT}{q} \)

- \( I_D = \text{diode current} \)
- \( v_D = \text{voltage across the diode} \)
- \( I_S = \text{Diode saturation current} \)
- \( k = \text{Boltzmann's constant } 1.38 \times 10^{-23} \text{ J/K} \)
- \( T = \text{absolute temp. } (273+t^\circ\text{C}) \)
- \( q = \text{electronic charge } (1.60 \times 10^{-19} \text{ coulomb}) \)

**Figure 4.7** The \( i-v \) characteristic of a silicon junction diode.
Terminal Characteristics of Junction Diodes

1. Forward bias region: \( v > 0 \)
2. Reverse bias region: \( v < 0 \)
3. Breakdown region: \( v < -V_{zk} \)

Figure 4.8 The diode \( i-v \) relationship with some scales expanded and others compressed in order to reveal details.
At a constant current, the voltage drop decreases by approximately 2 mV for every 1°C increase in temperature.

\[ V_T = \frac{kT}{q} \]

Figure 4.9 Temperature dependence of the diode forward characteristic. At a constant current, the voltage drop decreases by approximately 2 mV for every 1°C increase in temperature.
Figure 4.11 Graphical analysis of the circuit in Fig. 4.10 using the exponential diode model.
Figure 4.12 Development of the diode constant-voltage-drop model: (a) the exponential characteristic; (b) approximating the exponential characteristic by a constant voltage, usually about 0.7 V; (c) the resulting model of the forward–conducting diodes.
Example: Output 2.4V, current 1mA, diode voltage drop 0.7V, find R
Diode Small-Signal Model

![Diode Circuit Diagram](image)

\[ r_d = \frac{V_T}{I_D} \]

\[ r_d = \frac{1}{\left[ \frac{\partial I_D}{\partial V} \right]_{i_D=I_D}} \]
Example

\[ V = 10V + 1\sin(2\pi \cdot 60t) \]

![Diagrams](image)

(a)

(b)

(c)
Use Diode Forward Drop in Voltage Regulation.

\[ 10 \pm 1 \text{ V} \]

\[ R = 1 \text{ k}\Omega \]

\[ R_L = 1 \text{ k}\Omega \]

\[ +15 \text{ V} \]

\[ V_O \]

\[ I_L \]
Operation in the Reverse Breakdown Region

– Zener Diodes –

\[ I_Z \quad + \quad V_Z \quad - \]
Zener Diode Model

\[ V_Z = V_{Z0} + r_z I_Z \]

\[ \Delta V = \Delta I \cdot r_z \]

Slope = \( \frac{1}{r_z} \)

\( -V_Z \), \( -V_{Z0} \), \( -V_{ZK} \)

\( -I_{ZT} \) (test current)
Example: Shunt regulator zener diode
Use of Zener Diode

- Shunt Regulator
  - The diode is in parallel with the load

- Temperature Sensing
  - Using temperature coefficient (temco)
  - $-2 \text{mV/}^0\text{C}$
Rectifier Circuits

Friday Sept 26

Figure 4.20 Block diagram of a dc power supply.
The half-wave rectifier

Figure 4.21 (a) Half-wave rectifier. (b) Transfer characteristic of the rectifier circuit. (c) Input and output waveforms.
The full-wave rectifier

![Diagram of a full-wave rectifier utilizing a transformer with a center-tapped secondary winding.]

**Figure 4.22** Full-wave rectifier utilizing a transformer with a center-tapped secondary winding: (a) circuit; (b) transfer characteristic assuming a constant-voltage-drop model for the diodes; (c) input and output waveforms.

\[ PIV = 2v_S - V_D \]
The bridge rectifier

\[ \text{PIV} = v_S - V_D \]

Figure 4.23 The bridge rectifier: (a) circuit; (b) input and output waveforms.
Figure 4.24 (a) A simple circuit used to illustrate the effect of a filter capacitor. (b) Input and output waveforms assuming an ideal diode. Note that the circuit provides a dc voltage equal to the peak of the input sine wave. The circuit is therefore known as a peak rectifier or a peak detector.
Figure 4.25 Voltage and current waveforms in the peak rectifier circuit with $CR \gg T$. The diode is assumed ideal.
Figure 4.26 Waveforms in the full-wave peak rectifier.

\[ V_r = \frac{I_L}{2fC} \]

\[ I_L = \frac{V_p}{R} \]
Precision half-wave rectifier

(a) Circuit diagram

(b) Voltage transfer characteristic
Limiter Circuit

Figure 4.28 General transfer characteristic for a limiter circuit.

Figure 4.30 Soft limiting.
A variety of basic limiting circuits.
A variety of basic limiting circuits.
Example

Both diodes cut-off

\[ V_o = +5 + \frac{1}{2}(V_i - 5) \]
\[ V_o = 2.5 + \frac{1}{2}V_i \]

D1 on
\[ V_o = -5 + \frac{1}{2}(V_i + 5) \]
\[ V_o = -2.5 - \frac{1}{2}V_i \]

D2 on

Both diodes cut-off
The clamped capacitor or dc restorer with a square-wave input and no load.

(a) The input waveform $v_I$ with a square wave from $+4$ V to $0$ V to $-6$ V with a peak of $10$ V.

(b) The circuit diagram of the clamped capacitor with input $v_I$, capacitor $C$, and output $v_O$.

(c) The output waveform $v_O$ with a pulsating output of $10$ V.

The clamped capacitor with load resistance.

(a) The circuit diagram with a load resistor $R$.

(b) The input waveform $v_I$ with peaks labeled $V_a$.

(c) The output waveform $v_O$ with peaks labeled $V_a$ and times $t_0$, $t_1$, and $t_2$. 

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Voltage doubler: (a) circuit; (b) waveform of the voltage across $D_1$. 
Other Diode devices:

1. **Schottky-Barrier diode (SBD):**
   - Metal anode, semiconductor cathode
   - Fast switching ON/OFF.
   - Low forward voltage drop (0.3 – 0.5 V)

2. **Varactors:**
   - Capacitance between PN junction
   - Changing reverse voltage, changing capacitance

3. **Photodiodes:**
   - Reverse-biased PN junction illuminates
   - Converting light signal to electrical signal

4. **LEDs:**
   - Inverse function of photodiodes (electrical to light)
Summary (page 215, 216)

In the forward direction, the ideal diode conducts any current forced by the external circuit while displaying a zero voltage drop. The ideal diode does not conduct in the reverse direction; any applied voltage appears as reverse bias across the diode.

The unidirectional-current-flow property makes the diode useful in the design of rectifier circuits.

The forward conduction of practical silicon diodes is accurately characterized by the relationship \( i = I_S e^{\frac{V}{nV_T}} \).
A silicon diode conducts a negligible current until the forward voltage is at least 0.5 V. Then the current increases rapidly, with the voltage drop increasing by 60 mV to 120 mV (depending on the value of $n$) for every decade of current change.

In the reverse direction, a silicon diode conducts a current on the order of $10^{-9}$ A. This current is much greater than $I_s$ and increases with the magnitude of reverse voltage.

Beyond a certain value of reverse voltage (that depends on the diode) breakdown occurs, and current increases rapidly with a small corresponding increase in voltage.

Diodes designed to operate in the breakdown region are called zener diodes. They are employed in the design of voltage regulators whose function is to provide a constant dc voltage that varies little with variations in power supply voltage and/or load current.

A hierarchy of diode models exists, with the selection of an appropriate model dictated by the application.

In many applications, a conducting diode is modeled as having a constant voltage drop, usually approximately 0.7 V.

A diode biased to operate at a dc current $I_D$ has a small-signal resistance $r_d = n V_T / I_D$. 

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