Module 1

Semiconductor (pn-Junction) Diodes

What are they and what is their purpose?

Diodes are electronic "check valves" which allow current to flow freely in one direction, but block current flow in the opposite direction.

Essentially, they serve the same function in circuits, as the valves in your heart and veins do in your body.

How do they work? (Module 2)

Semiconductor (pn-Junction) Diodes

Physically, diodes are formed by the interface between two regions of oppositely doped semiconductor (i.e., pn junction) and are thus, structurally, the simplest semiconductor devices used in electronics.

Ideal Diode

An ideal diode is a two-terminal device defined by the following non-linear (current-voltage) iv-characteristic:

Note: From the above, it follows that zero power dissipation occurs in an ideal diode!
**Forward Biased Regime** \((v > 0)\): Zero voltage drop occurs across a forward-biased ideal diode \(i.e., \) the diode behaves like an ideal short circuit.

**Reverse Bias Regime** \((v \leq 0)\): Zero current flows in a reverse-biased ideal diode \(i.e., \) the diode behaves like an open circuit.

- Determine the polarity of the voltage across the diode, then “replace” the diode with its equivalent circuit (either open-cct. or short cct.) and proceed with linear circuit analysis.

### DC Behavior:

- **e.g.** The diodes in each of the following circuits can be assumed to be ideal.

  ![Diode Circuit Diagram](image)

  \(V = +10 \text{ V}\)

  \(I = 1 \text{ kΩ}\)

  \(D \text{ Fwd. biased}\)

  \(\therefore V = 0\)

  \(I = \frac{+10 \text{ V} - 0 \text{ V}}{1 \text{ kΩ}} = 10 \text{ mA}\)

  \(V = +10 \text{ V} - (0 \text{ A})(1 \text{ kΩ}) = 10 \text{ V}\)

- **e.g.** The diodes in each of the following circuits can be assumed to be ideal, and the voltages \(v_A\) and \(v_B\) can be either +5 V or 0 V.

  ![Diode Circuit Diagram](image)

  \(v_A\) \(v_B\) \(v_Y\)

  \|\|\|

  0 \hspace{1cm} 0 \hspace{1cm} 0

  0 \hspace{1cm} 5 \hspace{1cm} 0

  5 \hspace{1cm} 0 \hspace{1cm} 0

  5 \hspace{1cm} 5 \hspace{1cm} 5

  \(v_Y = v_A \cdot v_B\) AND Gate

  ![Diode Circuit Diagram](image)

  \(v_A\) \(v_B\) \(v_Y\)

  \|\|\|

  0 \hspace{1cm} 0 \hspace{1cm} 0

  0 \hspace{1cm} 5 \hspace{1cm} 5

  5 \hspace{1cm} 0 \hspace{1cm} 5

  5 \hspace{1cm} 5 \hspace{1cm} 5

  \(v_Y = v_A + v_B\) OR Gate

  Alternatively,

  \(v_Y = v_A \cdot v_B \cdot v_C\)

  \(v_Y = v_A + v_B + v_C\)
AC Behavior:

* e.g. The diode in the following circuit can be assumed to be ideal.
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Consider the current flowing in the following circuit where the diode is ideal and $v_S = 24 \sin(\omega t)$ V.

The diode begins to conduct when $v_S = 12$ V.

The voltage across the resistor has the same waveform as the current (i.e., remaining zero until $v_S = 12$ V). The amplitude (i.e., maximum) load voltage is thus

$$V_R = V_S - 12 \text{ V} = 24 \text{ V} - 12 \text{ V} = 12 \text{ V}.$$
Conduction Angle:

Consider the current flowing in the following circuit where the diode is ideal and \( v_S = 24 \sin(\omega t) \) V.

The diode begins to conduct when \( v_S = 12 \) V, which occurs at a phase angle defined by \( 24 \sin(\omega t) = 12 \) V. Or, in terms of the conduction \( 2\theta \) as defined in the figure above,

\[
24 \sin\left(\frac{\pi}{2} - \theta\right) = 12 \text{ V}
\]

or\[
24 \cos(\theta) = 12 \text{ V}
\]

\[
\therefore \quad 2\theta = 2 \cos^{-1}\left(\frac{12 \text{ V}}{24 \text{ V}}\right) = 120^\circ
\]

The conduction angle characterizes the fraction of a period that the diode is “on”.

Real Diode

The physics of real \( pn \)-junctions leads to the following (non-ideal) \( iv \)-characteristic:

Note that real diodes exhibit three distinct operating regions (cf. two for the ideal diode)!
Forward (FWD) Bias Regime ($v > 0$):

The $iv$-characteristic in this region is closely approximated by the exponential relation,

$$i = I_s \left( e^{v/nV_T} - 1 \right)$$

“Diode Equation”

where:

- $I_s = Reverse$ Saturation Current (also called Scale$ Current in S&S text, since $I_s \propto A_{jctn}$). Typically, $I_s$ is very small: pA for discrete silicon diodes, fA for integrated circuit diodes;

- $n$ = empirical constant (typically $1 \leq n \leq 2$, depending on the type of diode and its physical structure);

- $V_T =$ Volt-Equivalent of Temperature or Thermal Voltage defined by

$$V_T = kT/q$$

where:

- $k =$ Boltzmann’s constant (also written $k_B$) = 1.38x10^{-23} \text{ J/K};$

- $T =$ Absolute Temperature (K);

- $q =$ Electronic Charge = 1.602 x 10^{-19} \text{ C}.$

$e.g.$ At 20 °C, $V_T \approx 25.2 \text{ mV} = 25 \text{ mV}$ (used throughout S&S text and this course).
Clearly, for larger currents (where \( i >> I_S \) or \( v > 10 nV_T \)), the diode equation simplifies slightly to

\[
i = I_S e^{v/nV_T}
\]

which is the form most commonly used to describe forward-biased diode currents larger than a few \( \mu A \).

Values of \( I_S \) and \( n \) are normally specified by the diode manufacturer. However, \( I_S \) and \( n \) can be determined empirically if 2 measured operating points \( (I_1, V_1) \) and \( (I_2, V_2) \), are available; if a reasonable estimate for \( n \) is available, then 1 measured operating point is sufficient. In this course, if \( n \) is not given (or not computable from available data), assume \( n=1 \).

**Reverse (REV) Bias Regime \((-V_ZK \leq v \leq 0)\):**

The reverse diode current is also described by \( i = I_S \left( e^{v/nV_T} - 1 \right) \), however, \( e^{v/nV_T} \to 0 \) when \( v \ll 0 \), thus the diode equation reduces to

\[
i \approx -I_S
\]

so the current “saturates” at \(-I_S\) when the diode is significantly reverse biased (and hence the name *Reverse Saturation Current*).

The diode equation is valid throughout the *forward bias* and *reverse bias* regions of the *i*-\*v*-characteristic:*
Breakdown (BKD) Regime ($v \leq -V_{ZK}$):

A reversible breakdown occurs when $v < -V_{ZK}$, which gives rise to the steep gradient in the $iv$-characteristic in this region.

There are actually two distinct breakdown mechanisms:

1. Zener breakdown (predominates if $-5 \leq -V_{ZK} \leq -2 \text{ V}$) - due to excess carriers generated by direct disruption of covalent bonds caused by extremely high $E$-field within depletion region of highly doped semiconductors;

2. Avalanche Breakdown (predominates if $-V_{ZK} < -7 \text{ V}$) - due to excess carriers generated by collision-induced ionization in depletion region of lightly doped semiconductors.

A combination of these mechanisms is usually responsible in diodes where $-7 \leq -V_{ZK} \leq -5 \text{ V}$.

Typical diodes used in signal processing applications have $-V_{ZK} < -30 \text{ V}$ and are optimized for FWD or REV bias operation. However, some diodes are specifically designed for operation in the BKD regime. Diodes optimized for operation in the breakdown regime are typically called Zener diodes, regardless of which mechanism dominates.

Detail of diode $iv$-characteristic in the breakdown regime:

All real diodes exhibit this behavior, but only Zener diodes are normally operated in the breakdown regime.

Note the opposite polarity convention compared to signal diodes (since Zener diodes are almost always reverse biased).

Note also that the current-voltage behavior of Zener diodes in the reverse bias and forward bias regimes is the same as for signal diodes.
Temperature Dependence:

Forward Bias Regime: At a given (constant) diode current, v exhibits an approximately linear shift in the iv-characteristic due to the combined effect of the temperature dependences of both \( I_S \) and \( V_T \).

\[ \text{Rule of Thumb: Typically, the } iv\text{-characteristic shifts approximately } -2 \text{ mV/}^\circ C. \]

Reverse Bias Regime: The temperature dependence of the reverse current is that of \( I_S \) alone, which changes exponentially as a function of temperature.

\[ \text{Rule of Thumb: Typically, } I_S \text{ approx. doubles for every } 10 \text{ }^\circ C \text{ increase in Temperature.} \]

These variations may lead to significant changes in the operation of a circuit over a large temperature range and, in many applications, requires compensation strategies to be implemented in the design of some circuits.

In this course, unless stated otherwise, assume that the temperature remains constant at ~300 K (Room temperature).

Breakdown Regime: The temperature coefficient (TC) of Zener diodes depends on both voltage and current and, like in the FWD bias regime, leads to an approximately linear shift in the iv-characteristic.

In this regime, however, the TC > 0, at least over an appreciable range of currents.

\[ \text{e.g., A } 6.8 \text{ V Zener diode exhibits a } \text{TC=+2 mV/}^\circ C, \text{ which is complementary to a forward biased diode!} \]

This leads to a popular strategy for compensating for the temperature dependence of Zener diodes depicted below:

\[ \text{Here, the diode current is nearly independent of } T \text{ (over a useful range of } i). \]

Commercially available Zener diodes are often packaged in this configuration.
**Analysis of Diode Circuits**

e.g. Consider the following circuit where the diode is to be treated as real:

\[
\begin{align*}
V_{DD} & + \\
10 \text{ k}\Omega & \quad R \quad + \\
V & \quad + \\
10 \text{ V} & \quad - \\
\end{align*}
\]

\[V_{DD} = IR + V \quad (1)\]

\[I = I_s \left(e^{\frac{V}{nV_T}} - 1\right) \quad (2)\]

**Exact Solution:** If \(I_s\) and \(n\) for the diode are known, then (1) and (2) can be solved simultaneously to obtain \(I\) and \(V\).

**Graphical Solution:** If data are available, then (1) and (2) could be plotted and \(I\) and \(V\) could be obtained from the intersection.

**Approximate Solution:** If an exact solution is not required, an approximation can be found using an iterative approach.

e.g. Suppose the diode is specified as exhibiting a 0.7 V drop at 1 mA (in the textbook, this is sometimes called “a 1-mA diode” for short), with \(n = 1.8\).

**step 0**) Assume that the diode can be adequately described by \(I \equiv I_s e^{\frac{V}{nV_T}} \quad (2')\)

Substitute \(I = 1\) mA and \(V = 0.7\) V (from specs.) to calculate \(I_s\)

\[I_s = 10^{-3} e^{-0.7/nV_T}\]

which yields

\[I = 10^{-3} e^{\frac{(V-0.7)}{nV_T}} \quad \text{or} \quad V = nV_T ln(1/10^{-3}) + 0.7 \quad (2'')\]

**step 1**) As a first guess/approximation, assume \(V = 0.7\) V, then

\[I = \frac{V_{DD} - V}{R} = \frac{10 \text{ V} - 0.7 \text{ V}}{10 \text{ k}\Omega} = 0.93 \text{ mA}\]
The accuracy can be improved by iterating between (1) and (2'') as follows:

step 2) Substitute the value of I found in step 1 into (2'') to calculate a new value for V

\[ V = (1.8)(0.025)\ln(0.93) + 0.7 = 696.7 \text{ mV} \]

step 3) Substitute this value back into (1), to calculate a new value for I

\[ I = \frac{10 \text{ V} - 0.697 \text{ V}}{10 \text{ k}\Omega} = 0.9303 \text{ mA} \]

step 4) Continue iterating between (1) and (2'') until

\[ \left( \frac{I_n - I_{n-1}}{I_n} \right) \leq 1\% \quad \text{(arbitrary precision)} \]

Graphical representation of iterative method:

Alternatively, appropriate simplifying assumptions can yield an approximate solution that, while not as accurate, may be good enough for many applications!

Recall: \[ i = I_s \left( e^{v/nV_T} - 1 \right) \quad \text{“Diode Equation”} \]

Large-Signal Diode Models (for approximate analyses):

The choice of which model to apply in a given design/analysis depends on the operating point of the diode and the magnitude of the other voltages and currents in the circuit.
Linearized (large-signal) models of the diode forward bias characteristics superimposed on an exponential real diode characteristic. (a) Constant-Voltage-Drop model; (b) Piecewise-Linear (“Battery-plus-Resistance”) model.

Simplified Exponential: Accurate if $i_D >> I_S$ (e.g., >μA); useful for iterative analyses.

Ideal Diode: Adequate if $v_D$ is small compared to other voltages in the circuit; also useful for qualitative analysis of circuit operation.

Constant-Voltage-Drop: Reasonable approximation at higher currents.

Piecewise-Linear: Reasonable approximation for “mid-range” currents (deviates rapidly at currents higher or lower than intersection points with true characteristic).

Small-Signal Diode Model:

Consider the following circuit:

The expression for $i_D(t)$ can be expanded in a Taylor series about the operating point to obtain

$$i_D(t) \approx I_D \left( 1 + \frac{v_d(t)}{nV_T} \right) \text{ Small-Signal Approximation}$$

Recall: $f(x) = f(x_0) + \frac{(x-x_0)}{0!} f'(x_0) + \frac{(x-x_0)^2}{1!} f''(x_0) + \cdots$ Taylor’s Series

where $I_D = I_S e^{V_D/nV_T} = \text{diode current when } v_d(t) = 0$,

which remains a good approximation provided

$$\frac{v_d}{nV_T} << 1 \quad (e.g., \ v_d < 10 \text{mV at } 20 \degree \text{C for a diode with } n=2)$$
Thus, superimposed on the dc current \( I_D \), is a small-signal ac current \( i_d(t) \) such that

\[
i_D(t) = I_D + i_d(t)
\]

where

\[
i_d(t) = \frac{I_D}{nV_T} v_d(t)
\]

Notice that the term \( I_D/nV_T \) has the dimensions of conductance, and hence

\[
g_d = \frac{I_D}{nV_T} = \text{Small-Signal Conductance}
\]

or

\[
r_d = \frac{nV_T}{I_D} = \text{Small-Signal Resistance}
\]

Sometimes \( r_d \) is also called the Incremental Resistance.

e.g., A voltage-controlled attenuator (see separate notes posted on WWW site).

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### Diode Applications: Power Supplies

Consider the following DC power supply network:

![Power Supply Diagram]

Require a simple circuit that removes as much of the residual "ripple" as possible from a power supply.

e.g., A simple diode “voltage regulator”:

Consider the following circuit where each of the (identical) diodes are characterized by \( V = 0.7 \text{ V} \) @ \( I = 1 \text{ mA} \) and \( n = 2 \). Determine \( v_O = V_D + v_d \) with no load \( (R_L = \infty) \).
Given that, for each diode, \( V = 0.7 \text{ V} @ I = 1 \text{ mA} \) and \( n = 2 \), \( I_s \) can be computed and \( V_D \) can be found using an iterative analysis:

\[
I_s = (1 \text{ mA}) e^{(0.7 \text{ mV})(2)(25 \text{ mV})} = 8.3 \times 10^{-7} \text{ mA}
\]

Initial estimate for individual diode voltages, \( V_D' = -0.7 \text{ V} \)

\[
V_D = 3 \times (0.7 \text{ V}) = 2.1 \text{ V} \quad \rightarrow \quad I_D = \frac{10V - 2.1V}{1 \text{ k}\Omega} = 7.9 \text{ mA}
\]

new \( V_D' = (2)(25 \text{ mV}) \ln \left( \frac{7.9 \text{ mA}}{8.3 \times 10^{-7} \text{ mA}} \right) = 0.803 \text{ V} \)

\[
V_D = 3 \times (0.803 \text{ V}) = 2.41 \text{ V} \quad \rightarrow \quad I_D = \frac{10V - 2.41V}{1 \text{ k}\Omega} = 7.59 \text{ mA}
\]

new \( V_D' = (2)(25 \text{ mV}) \ln \left( \frac{7.59 \text{ mA}}{8.3 \times 10^{-7} \text{ mA}} \right) = 0.801 \text{ V} \quad (<1\% \text{ change} \text{ in} \ V_D' \text{ so close enough})
\]

\[
r_d = \frac{nV_I}{I_D} = \frac{(2)(25 \text{ mV})}{7.59 \text{ mA}} = 6.59 \Omega
\]

\[
\nu_d = \pm (1 \text{ V}) \frac{3r_d}{R + 3r_d} = \pm 19.4 \text{ mV}
\]

\[
\therefore \quad V_O = V_D + \nu_d = 2.41 \text{ V} \pm 19.4 \text{ mV} = 2.41 \text{ V} \pm 0.8 \%
\]

So the fluctuations in the output voltage have been reduced by ~10x compared to the input voltage!

Recall that the \( iv \)-characteristic of diodes operating in the breakdown regime is essentially linear!

\[
V_Z = V_{Z0} + r_Z i
\]

\[
r_Z = \text{Constant}
\]

\( -V_{ZK} \) can be “tailored” during manufacture and an extensive array of Zener diodes with different \( -V_{ZK} \) values (Q points) are commercially available.
e.g., A Zener diode “voltage regulator”:

Consider the following circuit where the Zener diode is characterized by $V_{ZK} = 6.69 \, \text{V}$, $I_{ZK} = 0.2 \, \text{mA}$, $r_Z = 20 \, \Omega$ and $V_Z = 6.8 \, \text{V} @ I_Z = 5 \, \text{mA}$. Determine (a) $V_O$ when $R_L = \infty$ (no load), (b) $R_{L(\text{min})}$ (the maximum load), (c) the Line Regulation and Load Regulation.

\[ V_Z = 6.8 \, \text{V} - (20 \, \Omega)(5 \, \text{mA}) = 6.7 \, \text{V} \]

\[ V_{Z0} = 6.8 \, \text{V} \]

\[ I_L = I_Z = \frac{V - V_{Z0}}{R + r_Z} = \frac{10 \, \text{V} - 6.7 \, \text{V}}{500 \, \Omega + 20 \, \Omega} = 0.0635 \, \text{mA} = 6.35 \, \text{mA} \]

\[ V_O = V_Z = V_{Z0} + r_Z I_Z = 6.7 \, \text{V} + (20 \, \Omega)(6.35 \, \text{mA}) = 6.83 \, \text{V} \]

Alternatively, using the Superposition Principle, $V_O$ under arbitrary load conditions is given by

\[ V_O = V_{Z0} \frac{R || R_L}{R || r_Z + R || R_L} + V \frac{r_Z || R_L}{R + r_Z || R_L} \]

and hence when $R_L = \infty$, this expression simplifies to

\[ V_O = V_{Z0} \frac{R}{r_Z + R} + V \frac{r_Z}{R + r_Z} = 6.83 \, \text{V} \]

(b) The Zener must remain in BKD, which requires that $I_Z \geq I_{ZK}$ under all load conditions. The maximum load $R_L = R_{L(\text{min})}$, therefore occurs when $I_Z = I_{ZK}$ & $V_Z = V_{ZK}$, and when the supply voltage $V = 9 \, \text{V}$.

\[ I_L = I_Z = \frac{V - V_{ZK}}{R} = \frac{9 \, \text{V} - 6.69 \, \text{V}}{500 \, \Omega} = 0.2 \, \text{mA} = 4.42 \, \text{mA} \]

\[ R_{L(\text{min})} = \frac{V_{ZK}}{I_L} = \frac{6.69 \, \text{V}}{4.42 \, \text{mA}} = 1.51 \, \text{k}\Omega \]

(c) The Line Regulation & Load Regulation are figures of merit that characterize the performance of the voltage regulator.

\[ \text{Line Regulation} = \frac{\Delta V_O}{\Delta V} \bigg|_{I_L = \text{constant}}, \quad \text{Load Regulation} = \frac{\Delta V_O}{\Delta L} \bigg|_{V = \text{constant}} \]
In order to compute these figures of merit quantitatively, it is useful to write an expression for $V_O$ that includes $I_L$ explicitly.

Applying KCL at the node,

$$I = I_L + I_Z$$

or

$$\frac{V - V_O}{R} = I_L + \frac{V_O - V_{Z0}}{r_Z}$$

or

$$V_O = V_{Z0} \frac{R}{R + r_Z} + V \frac{r_Z}{R + r_Z} - I_L (r_Z || R)$$

Thus, for the configuration considered here,

$$\text{Line Regulation} = \left. \frac{\Delta V_O}{\Delta V} \right|_{I_L \text{ constant}} = \frac{r_Z}{R + r_Z} = \frac{20 \Omega}{500 \Omega + 20 \Omega} = 38.5 \text{ mV} / \text{V} \quad \text{or} \quad 0.563 \%$$

$$\text{Load Regulation} = \left. \frac{\Delta V_O}{\Delta I_L} \right|_{V \text{ constant}} = -(r_Z || R) = \frac{(20 \Omega)(500 \Omega)}{(20 \Omega) + (500 \Omega)} = -19.23 \text{ V} / \text{A}$$

Note that the Load Regulation is independent of $R_L$.

Recall: DC power supply network

Require a circuit that "rectifies" (i.e., converts) an AC (bipolar) waveform to a rectified, monopolar waveform.

Rectifier diodes used in power supply applications are typically modeled using either ideal diodes or a constant-voltage-drop (CVD) model.
Simple Full-Wave Rectifier:

(a) Using a Center-Tapped Transformer + 2 (Real) Diodes

\[ V \text{ across } D_1 > 0 \text{ when } V \text{ across } D_2 < 0 \text{ and } V \text{ across } D_1 < 0 \text{ when } V \text{ across } D_2 > 0, \]
both \( D_1 \) & \( D_2 \) conduct current through \( R \) in the same direction (when forward biased).

Advantage:
- simple—only 2 diodes required

Disadvantage:
- each half of the secondary is connected to the load only half of the time

Peak Inverse Voltage:
- \( PIV = 2V_S-V_D \) (if CVD model)
- \( PIV = 2V_S \) (if diodes ideal)

(b) Using a Simple Transformer + 4 (Real) Diodes

\[ V \text{ across } D_1 \text{ & } D_2 > 0 \text{ when } V \text{ across } D_3 \text{ & } D_4 < 0 \text{ and } V \text{ across } D_3 \text{ & } D_4 > 0 \text{ when } V \text{ across } D_1 \text{ & } D_2 < 0, \]
current through \( R \) is always in same direction.

Advantages:
- no center-tap is required and fewer turns are required on the secondary winding
- the PIV is lower than 2-Diode configuration
- more efficient (the transformer secondary winding is always connected to the load)

Disadvantages:
- common ground can not exist between the transformer secondary winding and load, \( R \)
Recall: DC power supply network

Require a circuit that "smoothes" the output waveforms from the rectifier circuit.

Consider the following HW rectifier circuit where the load resistance has been replaced by a capacitor:

If the diode and capacitor can both be considered to be ideal, then the capacitor charges to $V_p$ and the output voltage remains clamped at $V_p$. This circuit can be viewed as a "peak detector" (with an infinite load resistance).

In practical circuits, some finite load resistance always exists (e.g., the input impedance of subsequent stages), through which $C$ can discharge during the diode "off cycle".

This circuit is, essentially, a low-pass filter which attenuates the harmonics left in the rectified AC waveform on the cathode side of the diode.

A piecewise approximate analysis of this prototypical peak rectifier yields several equations useful for the design/analysis of DC power supply circuits (see separate set of notes on WWW site).
Diode Applications: Waveshaping Circuits

Consider the following alternative diode-capacitor configurations: e.g., Clamped-Capacitor DC Restorer (another bipolar-to-monopolar converter).

(a) If all components are ideal,

Here, \( D \) is forward biased only when \( v_i < v_c \). Hence, \( C \) charges to the most negative peak of \( v_i \) (during the first few cycles) and \( D \) remains reverse biased thereafter.

If \( D \) is reversed,

(b) If \( R \ll \infty \) and, \( V_{D0} \) & \( r_D > 0 \), but the capacitor is still ideal,

Assume \( V_{D0} = 0.7 \) V, and a steady state output waveform has been reached.

During the positive part of the input waveform (when \( D \) is reverse biased), \( C \) discharges through \( R \) such that

\[
V_O(t) = 4V + \left[ -4V - (-4V - 5.3V)e^{-(t-t_0)/\tau_1} \right] = (9.3V)e^{-(t-t_0)/\tau_1}; \quad t_0 \leq t \leq t_1
\]

where \( \tau_1 = RC \). During the negative part of the input waveform, \( C \) recharges through \( r_D \) such that

\[
V_O(t) = -6V + \left[ 5.3V - (5.3V - 9.3V)e^{-(t-t_0)/\tau_1}e^{-(t-t_2)/\tau_2} \right] = -0.7V - (9.3V - 9.3V)e^{-(t-t_1)/\tau_1}e^{-(t-t_1)/\tau_2}; \quad t_1 \leq t \leq t_2
\]

where \( \tau_2 = (r_D||R)C \). Normally, one would try to arrange that \( r_D << R \).
Consider a “clamped-capacitor” cascaded with a “rectifier/peak detector” as shown:

Here, the clamping circuit comprised of $C_1$ and $D_1$ determines $v_{D1}$, which becomes the input to the peak rectifier/detector comprised of $C_2$ and $D_2$.

If $C_1$ and $D_1$ are ideal, then $C_1$ will charge to $V_p$, which provides a dc offset of $-V_p$ to the signal passed to the peak rectifier and $C_2$ will charge to $-2V_p$ (i.e., the negative "peak" voltage passed from the clamp). And if $C_2$ and $D_2$ are ideal, then $V_O = -2V_p = \text{constant}$.

Limiting or Clipping Circuits:

The general transfer characteristic of a limiter circuit is described by

$$v_o = K v_i; \quad L_-/K \leq v_i \leq L_+/K \quad (i.e., \text{linear})$$

or, graphically,

Limiting circuits can be realized using regular or Zener diodes and resistors in various configurations.
e.g., Various diode limiter circuits.

Consider each of the following circuits where the diodes can be assumed to be adequately modeled using a constant-voltage-drop model with $V_D = 0.7 \, \text{V}$:

Other Types of Diodes

We have considered some of the common diode types (signal, rectifier, Zener) and applications (logic circuits, AC rectification, voltage regulation, waveshaping). However, there are numerous other specialized diode types that have been modified/adapted for other applications. For example...

Photodiodes:

Semiconductor devices are subject to optical charge carrier generation leading to generation of (usually) spurious or unwanted “photocurrents” when the diode is reverse biased. Therefore, most diodes are packaged in light blocking materials. However, some applications (e.g., solar cells, photodetectors) actually exploit these effects and diodes designed for such applications are packaged in transparent materials.

Light-Emitting Diodes (LEDs):

Conversely, some diodes actually emit light when forward biased, and this can be exploited for generating signals or optically-encoded information. Depending on material, colors from the infrared to the near ultraviolet may be produced; “white” LEDs are actually combinations of three LEDs of a different color, or employ coatings that filter the spectrum. An LED may be paired with a photodiode or phototransistor in the same package, to form an opto-isolator.
Schottky-Barrier Diodes:
These devices differ from other diodes in that their rectifying junction is formed by a special metal-semiconductor junction, instead of a standard $pn$-junction. Their forward voltage drop is typically in the range 0.15 V to 0.45 V, which makes them useful in voltage clamping applications; they can also be used as low-loss rectifiers, although their reverse leakage current is generally higher than $pn$-junction diodes. They also tend to have much lower capacitance than $pn$-junction diodes enabling fast switching speeds which are exploited in high-speed circuits and RF devices.

Esaki or Tunnel Diodes:
These diodes have a region in their iv-characteristic exhibiting negative resistance caused by quantum tunneling, allowing amplification of signals and very simple bistable circuits. These diodes are also the type most resistant to nuclear radiation.

Varactors:
These diodes exploit the voltage-dependent capacitances that are among the intrinsic properties of $pn$-junctions.

Etc.

*In order to appreciate the full potential of these “simplest” semiconductor devices, we must first understand their structure and physical operation...*