ENGR 305

Diodes

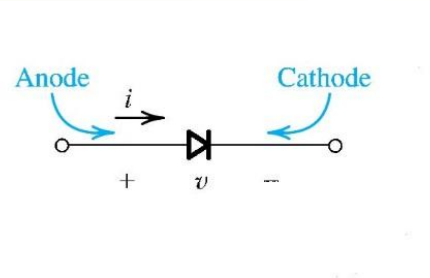
September 9, 2025

Diodes

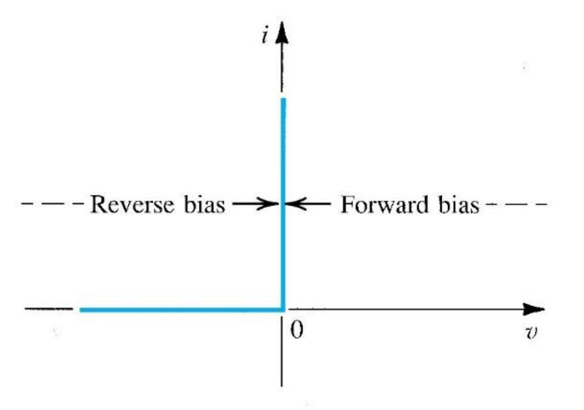
- In the past we used linear circuit amplification.
- There are many other signal-processing functions that require nonlinear circuits.
  - Generation of dc voltages from an ac power supply
  - Generation of signals of various waveforms
  - Digital logic and memory circuits
- The simplest and most fundamental nonlinear circuit element is the diode.
- We begin with a simplified model, a fictitious element, the ideal diode.
- Then we move on to the silicon junction diode.

The ideal diode

- This ideal diode is the most fundamental nonlinear circuit element.
- It is a two-terminal device with the circuit symbol shown in part (a)
- The current-voltage, or *i-v*, characteristic, is shown in part (b)



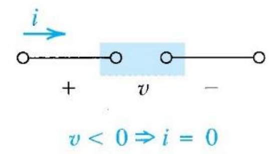
(a)



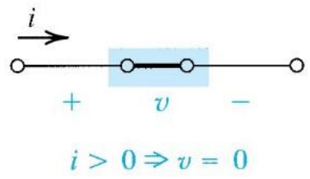
(b)

The ideal diode

- If a negative voltage is applied to the anode with respect to the cathode, no current flows
    - It behaves as an open circuit (part (c) of figure)
    - The diode is **reverse-biased.** The diode is **cut off.**
- If a positive voltage is applied to the anode with respect to the cathode, zero voltage drop appears across the diode.
    - The ideal diode behaves as a short circuit in the forward direction and is **forward-biased** (part (d) of figure) The diode is **on.**



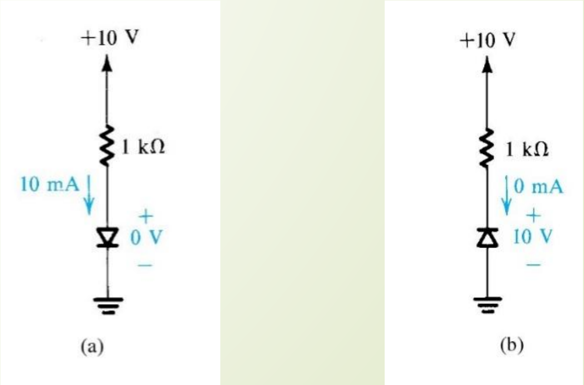
(c)



(d)

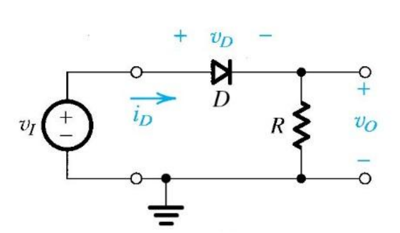
The ideal diode

- The circuit that is external to the diode must be designed to
  - Limit the forward current through a conducting diode
  - Limit the reverse voltage across a cutoff diode
- The diode in part (a) is conducting
  - The current through it is determined by the +10-V supply and the 1-kΩ resistor as 10 mA.
- The diode in part (b) is cut off, the current will be zero and the 10-V supply voltage appears as a reverse bias across the diode.
- The positive terminal is the **anode.**
- The negative terminal is the **cathode.**

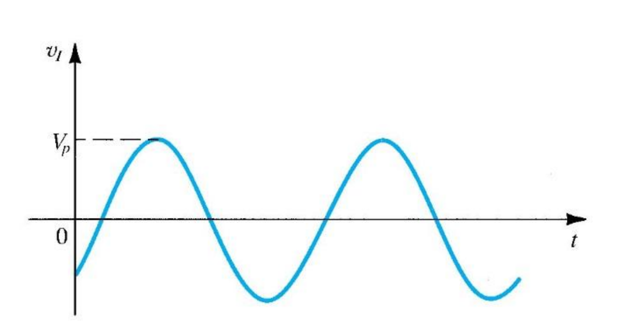


The rectifier

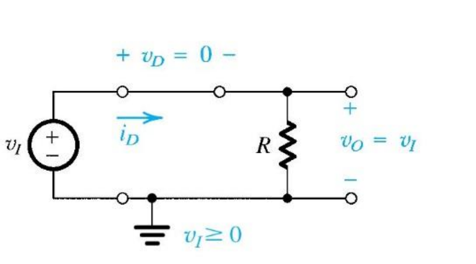
- The circuit consists of the series connection of a diode D and a resistor R.
- Let the input voltage v_I be the sinusoid shown.
  - During the positive half-cycles of the input sinusoid, the positive v_I will cause current to flow in the forward direction of the diode.
  - The circuit has the equivalent circuit shown in part (c).



(a)



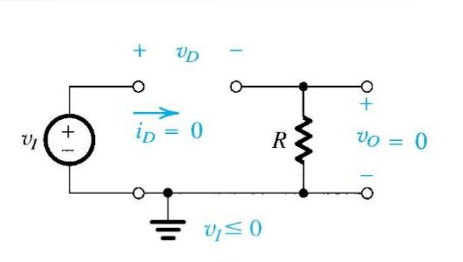
(b)



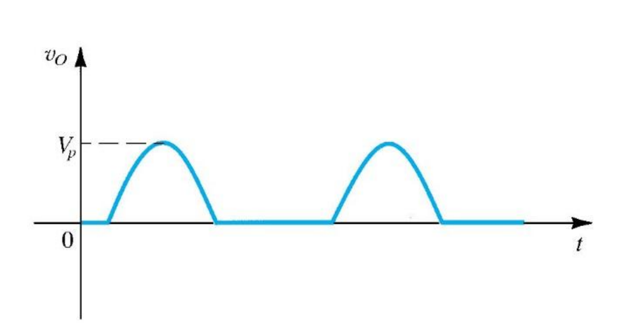
(c)

The rectifier

- During the negative half-cycles of v_I, the diode does not conduct.
- In this case the equivalent circuit is shown in part (d) and v_O is zero.
- The output has the waveform shown in part (e).
- While v_I alternates and has a zero average value, v_O is unidirectional and has a finite average value or *dc component*.



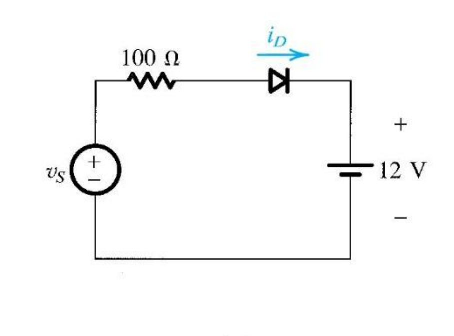
(d)



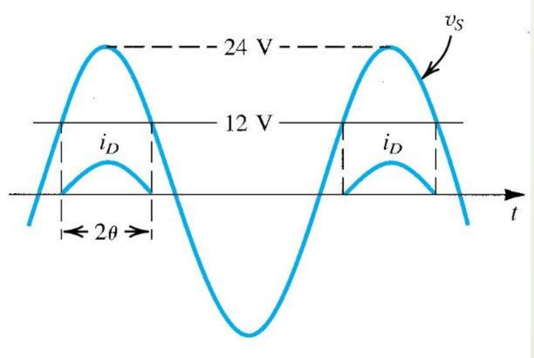
(e)

Example 4.1

- Part (a) of the figure shows a circuit for charging a 12-V battery. If $v_S$is a sinusoid with 24-V peak amplitude, find the fraction of each cycle during which the diode conducts.
- Also find the peak value of the diode current and the maximum reverse-bias voltage that appears across the diode.



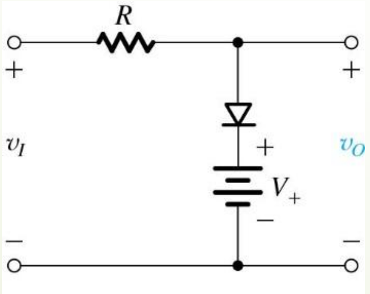
(a)



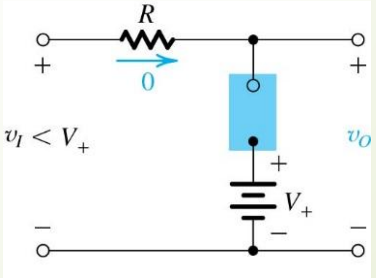
(b)

Limiting and protecting circuits

- A rearrangement of the circuit from the previous example results in a simple limiter circuit as shown in (a). Limiter circuits limit voltage excursions.
- When the input voltage v_I is below V_+, the diode is off and an open circuit.
- No current flows through the resistor R, and $v_O = v_I$.
- The equivalent schematic is shown in part (b).



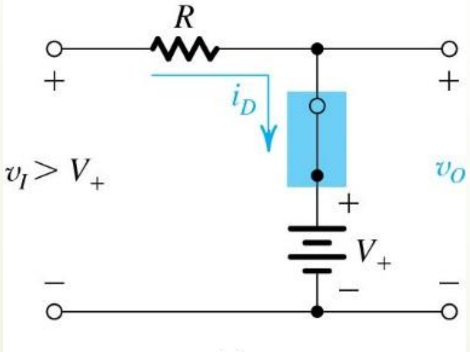
(a)



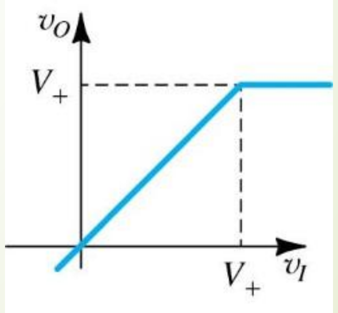
(b)

Limiting and protecting circuits

- When the input v_I exceeds V_+, the diode turns on, resulting in the circuit shown in part (c), where $v_O = V_+$.
- The circuit keeps v_O from exceeding the upper limit established by V_+.
  - The input-output characteristic is shown in part (d) of the figure.
  - When on the diode conducts a current $i_D = \frac{v_I - V_+}{R}$.



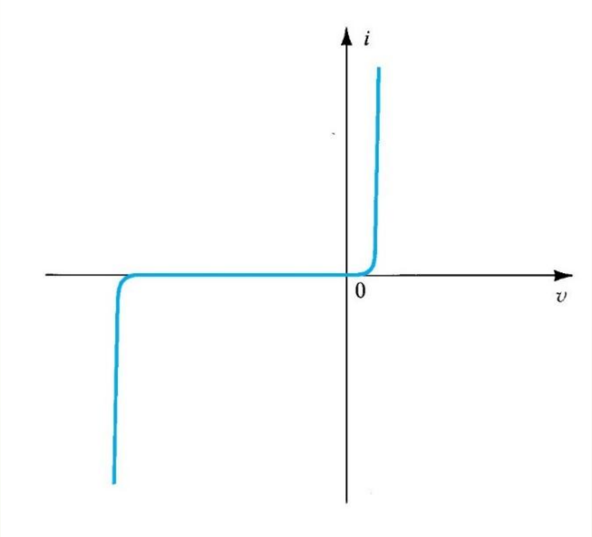
(c)



(d)

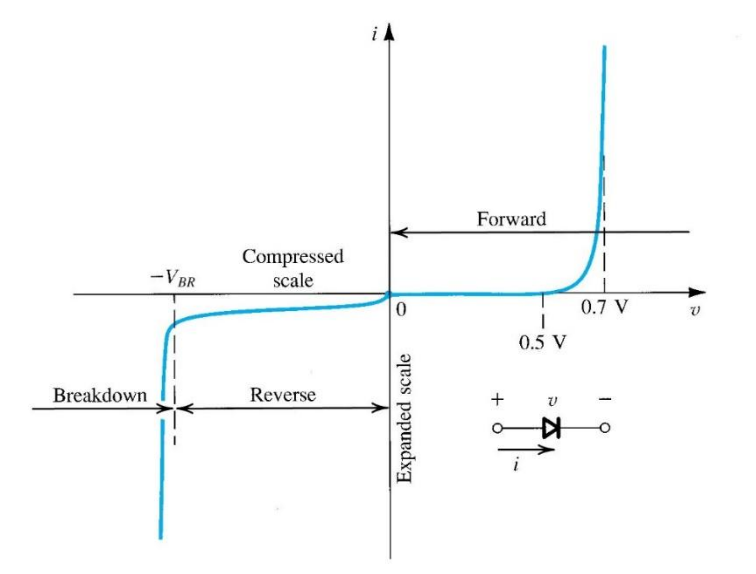
Terminal characteristics of junction diodes

- The most common implementation of the diode uses a *pn* junction.
  - We consider the *i-v*, or current-voltage, characteristics of the pn junction.
  - The pn junction can conduct substantial current in the forward direction.
  - It conducts almost no current in the reverse direction.



Terminal characteristics of junction diodes

- The characteristic curve consists of three distinct regions
  1. The forward-bias region, determined by $v > 0$
  2. The reverse-bias region, determined by $v < 0$
  3. The breakdown region, determined by $v < -V_{BR}$



The forward-bias region

- The diode is in the forward-bias region when the terminal voltage v is positive.
- In the forward region, the i-v relationship is approximated by
  - $i = I_S\left(e^{v/V_T} - 1\right)$
- In this equation, I_S is a constant for a given diode at a given temperature.
  - The current I_S is usually called the **saturation current.**
  - It is sometimes referred to as the **scale current.**
  - Doubling the junction area produces a diode with double the value of I_S.
  - For “small-signal” diodes, intended for low-power applications, I_S is on the order of 10^{-15} A.

Forward-bias region

- The voltage V_T is called the **thermal voltage** and is given by
  - $V_T = \frac{kT}{q}$
  - Where k = Boltzmann's constant = $8.62 \times \frac{10^{-5} eV}{K} = 1.38 \times 10^{-23} \text{joules/kelvin}$
  - T = absolute temperature in kelvins = 273 + temperature in $°C$
  - q = the magnitude of electronic charge = 1.60×10^{-19} coulomb
  - Substituting these gives a value $V_T = 0.0862T, mV$
  - At room temperature, we have $V_T \cong 25\ mV$

Forward-bias region

- For appreciable current *i* in the forward direction, where $i \gg I_S$, we can approximate it by the exponential relationship
  - $i \cong I_S e^{v/V_T}$
- We can rearrange this equation so that it is in the logarithmic form
  - $v = V_T ln \frac{i}{I_S}$
- The exponential relationship of the current *i* to the voltage v holds over a span of many decades of current.

Forward-bias region

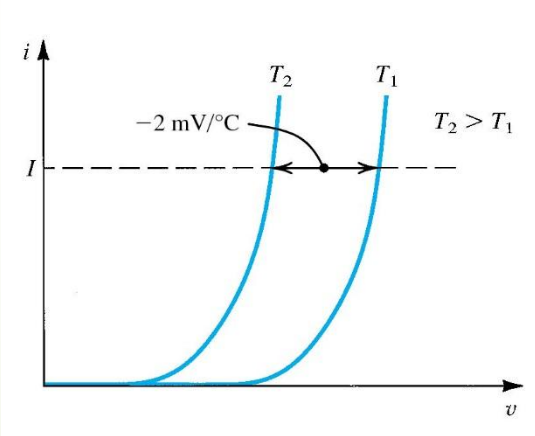
- Applying the *i*-v relationship to a diode with current I_1 and voltage V_1
  - $I_1 = I_S e^{V_1/V_T}$
- If the voltage is V_2, the diode current I_2 will be
  - $I_2 = I_S e^{V_2/V_T}$
- Taking the ratio of I_2 to I_1
  - $\frac{I_2}{I_1} = e^{(V_2 - V_1)/V_T}$
- This can be rewritten as $V_2 - V_1 = V_T \ln \frac{I_2}{I_1}$
- Putting this in terms of base-10 logarithms, $V_2 - V_1 = 2.3 V_T \log \frac{I_2}{I_1}$

Forward-bias region

- The equation states that for a decade change in current, the diode voltage drop changes by $2.3V_T$, which is approximately 60 mV.
- Referring to the *i*-v characteristic in the forward region, the current is negligibly small for voltages less than 0.5 V.
  - This voltage is referred to as the **cut-in voltage.**
- For a "fully conducting" diode, the voltage drop lies in a narrow range, 0.6-0.8 V.
- We use a simple "model" for the diode where we assume that a conducting diode has approximately a 0.7-volt drop across it.
- This 0.7-volt model applies to silicon diodes.

Temperature dependence of *i*-v curve

- Both I_S and V_T are functions of temperature
- The forward *i*-v characteristic varies with temperature
- At a given constant diode current, the voltage drop across the diode decreases by roughly 2 mV for every 1℃ increase in temperature.



Reverse-bias region

- When v becomes negative, the diode enters the reverse-bias region of operation.
- If the negative voltage v becomes a few times larger than V_T in magnitude, the exponential term becomes negligible compared to unity.
  - The diode current is then $i \cong -I_S$
- The current in the reverse direction is constant.
- This is where the term *saturation current* comes from.

Breakdown region

- The diode enters the breakdown region when the magnitude of the reverse voltage exceeds a threshold value that is specific to the particular diode
  - It is called the **breakdown voltage, or V_{BR}**
- In the breakdown region, the reverse current increases rapidly, and the increase in voltage drop is very small.
- Diode breakdown is normally not destructive, as long as the power dissipated in the diode is limited to a “safe” level.
- The safe values of current and power dissipation are specified on the device data sheets.