Part 1

Diodes

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EE2002 Analog Electronics

Lesson Objectives

At the end of this lesson, you should be able to:

- Describe ideal and real diodes
- Distinguish between an ideal diode under the reverse-biased situation and ideal diode under the forward-biased condition
- Discuss the regions of operation of the diode including forward-bias region, reverse-bias region and breakdown region
- Analyse the relationship between the current in the diode and voltage applied in diode and hence, the extraction of parameters for the diode formula with two sets of (I_D, V_D) given

Lesson Objectives

- Determine the Q-point or the values of I_{D} and V_{D} of diode by iteration method
- Analyse small-signal diode circuits to determine the dynamic resistance of the diode, if the Q-point and diode equation are known
- Explain the concept of diode rectifiers.

Outline

- Ideal Diodes
- Real Diodes
- Forward-bias and Reverse-bias of a PN Junction
- Terminal Characteristics of Junction Diodes
- Analysis of Diode Circuits
- Diode Rectifiers
- Elementary DC Power Supply
- Absolute Value Circuit

The Ideal Diode

The ideal diode is a two-terminal device having the circuit symbol and i-v characteristics shown in Figures1 and 2.

Forward-bias: $V_D = 0 \Rightarrow$ Diode behaves like a short circuit.

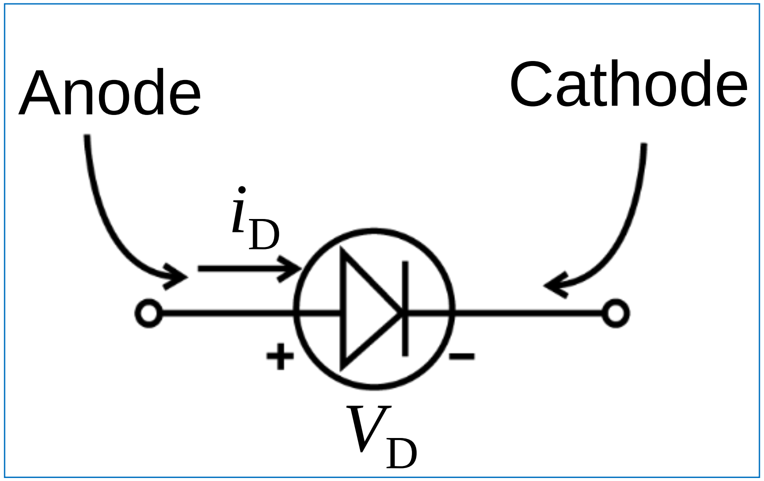


Figure 1. The ideal diode circuit symbol

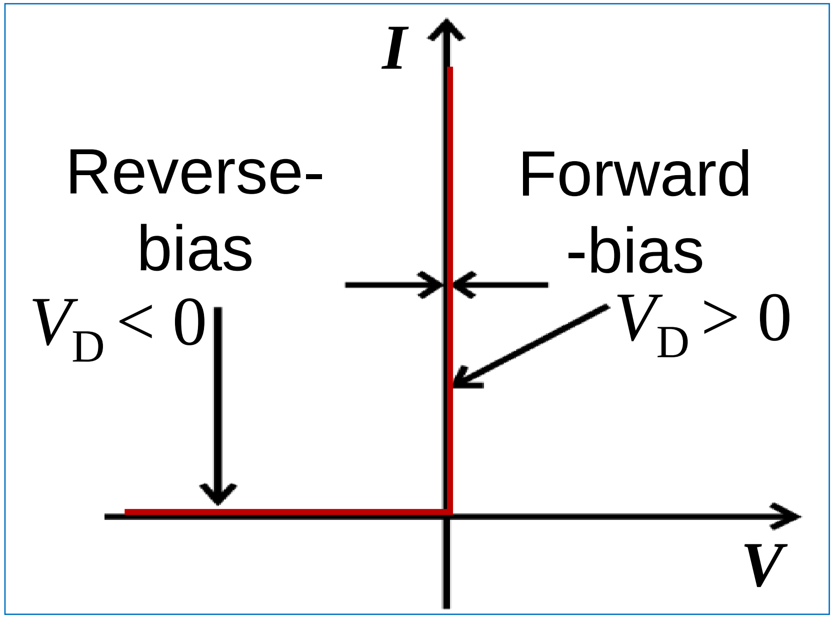


Figure 2. The ideal diode i-v characteristic.

The Ideal Diode

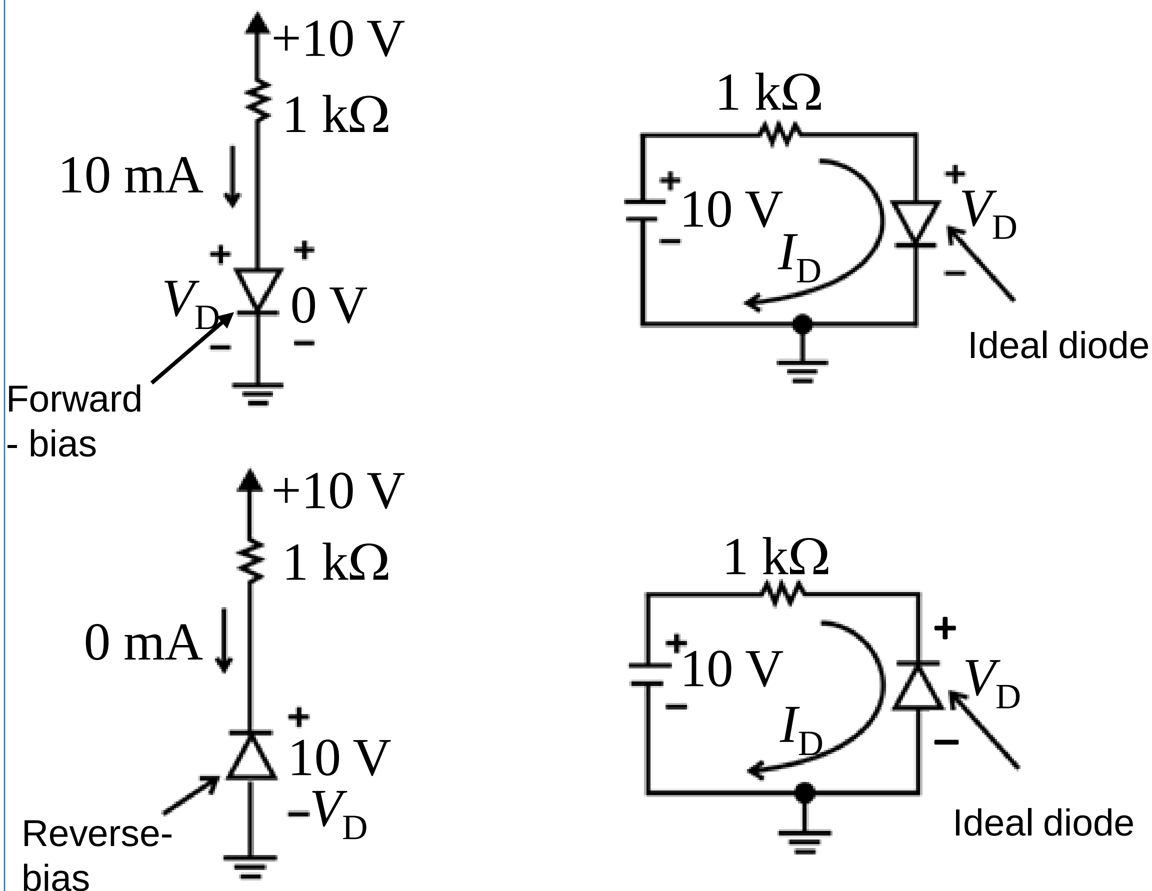
Under the reverse-biased condition,

$V_D < 0 \Rightarrow i_D = 0$ and the diode behaves as an open circuit.

Under the forward-biased condition,

- A positive current is applied to the ideal diode; $V_D \approx 0$ V appears across it.
- The ideal diode behaves as a short circuit in the forward direction and an open circuit in the reverse direction.

The Ideal Diode



$$I_D = \frac{10 - 0}{1\ \text{k}\Omega}$$

$$I_D = 10\ \text{mA}$$

$$V_D = 0$$

$$I_D = 0$$

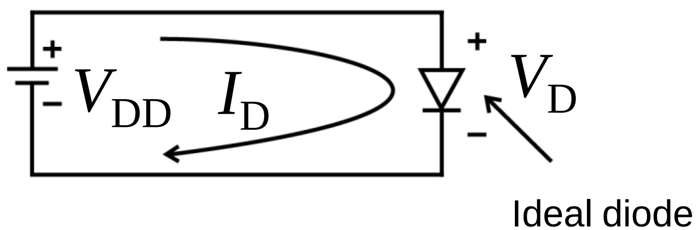
$$V_D = -10\ \text{V}$$

Figure 3. The two modes of operation of ideal diodes and the use of an external circuit to limit the forward current and the reverse voltage.

The Ideal Diode

Forward-bias vs Reverse-bias of an Ideal Diode

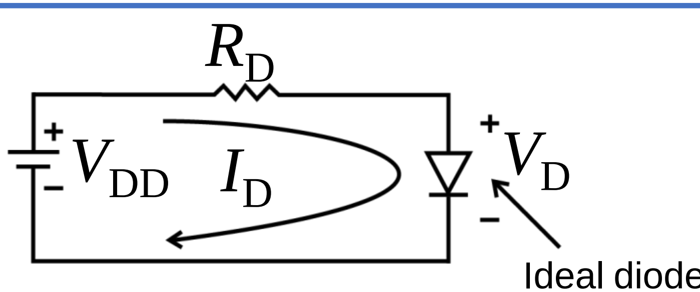
(i)



Forward-bias:

$V_D = 0$ V and $I_D = \infty$

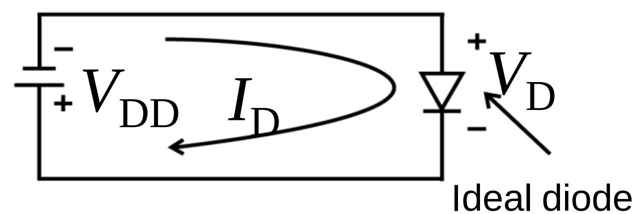
(ii)



Forward-bias:

$V_D = 0$ V and $I_D = V_{DD}/R_D$

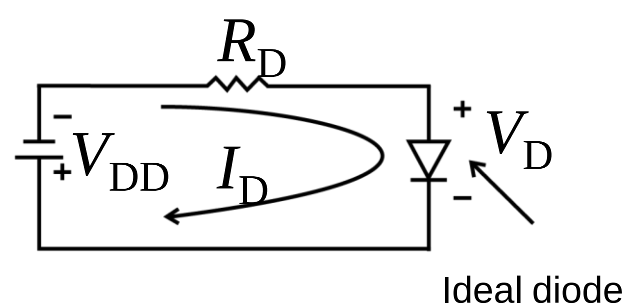
(iii)



Reverse-bias :

$I_D = 0$ and $V_D = -V_{DD}$

(iv)



Reverse-bias:

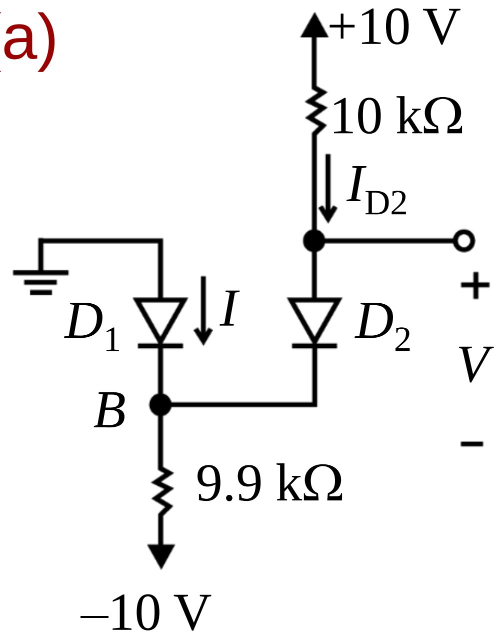
$I_D = 0$ and $V_D = -V_{DD}$

The Ideal Diode

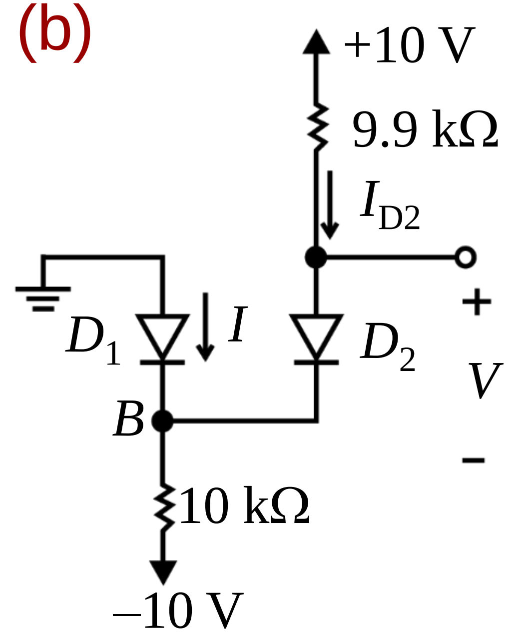
Example:

Assuming the diodes to be ideal, find the values of I and V in the circuit diagrams given below:

(a)



(b)



The Ideal Diode

Solution:

(A) Refer to the circuit in (a) and assume that both ideal diodes are conducting.

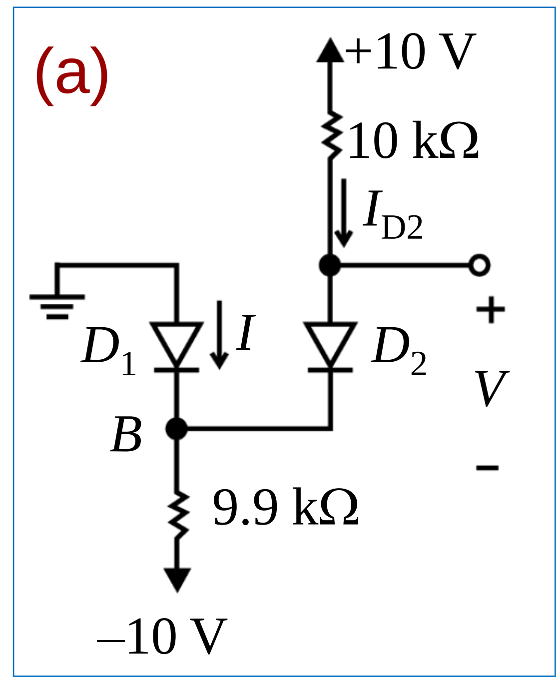
$$V_{D1} = V_{D2} = 0; \; V_B = 0; \; \boxed{V = 0}$$

$$I_{D2} = \frac{10 - 0}{10\ \text{k}\Omega} = 1.0\ \text{mA}$$

Using KCL at node B,

$$I + I_{D2} = \frac{0 - (-10)}{9.9\ \text{k}\Omega} = 1.01\ \text{mA}$$

$$\therefore \boxed{I = 0.01\ \text{mA}}$$

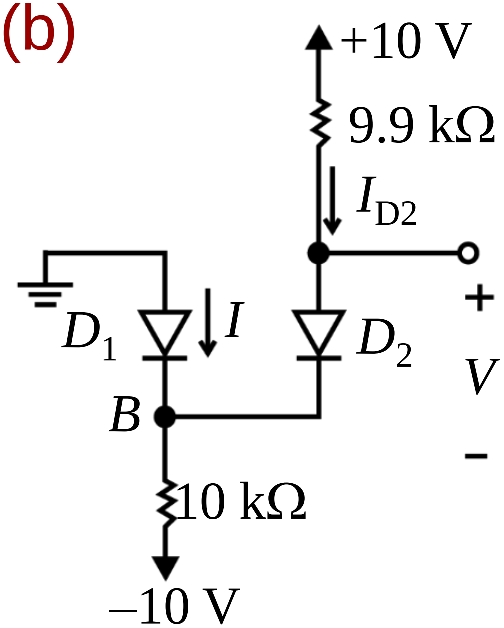


The Ideal Diode

Solution (Cont.):

(B) Refer to the circuit in (b) and assume that both ideal diodes are conducting.

(b)



$$V_B = 0; \ V = 0$$

$$I_{D2} = \frac{10 - 0}{9.9\ \text{k}\Omega} = 1.01\ \text{mA}$$

Applying KCL at node *B*,

$$I + I_{D2} = \frac{0 - (-10)}{10\ \text{k}\Omega} = 1.0\ \text{mA}$$

$$\therefore\ I = -0.01\ \text{mA}$$

This is impossible! The original assumption is not correct.

The Ideal Diode

Solution (Cont.):

Now, assuming D_1 is off and D_2 is on, then

$$I_{D2} = \frac{10 - (-10)}{19.9\ \text{k}\Omega} = 1.005\ \text{mA}$$

$$V_B = (1.005\ \text{mA} \times 10\ \text{k}\Omega) + (-10\ \text{V})$$
$$= 0.05\ \text{V}$$

The diode D_1 is reverse-biased as assumed, and

$$\boxed{I = 0}$$

$$\boxed{V = +0.05\ \text{V}}$$

Real Diodes

What is a pn junction diode ?

- A pn junction diode is a two-terminal semiconductor device having circuit symbol as shown in Figure 4.

- The pn junction is produced by placing a layer of p-type semiconductor next to a layer of n-type semiconductor.

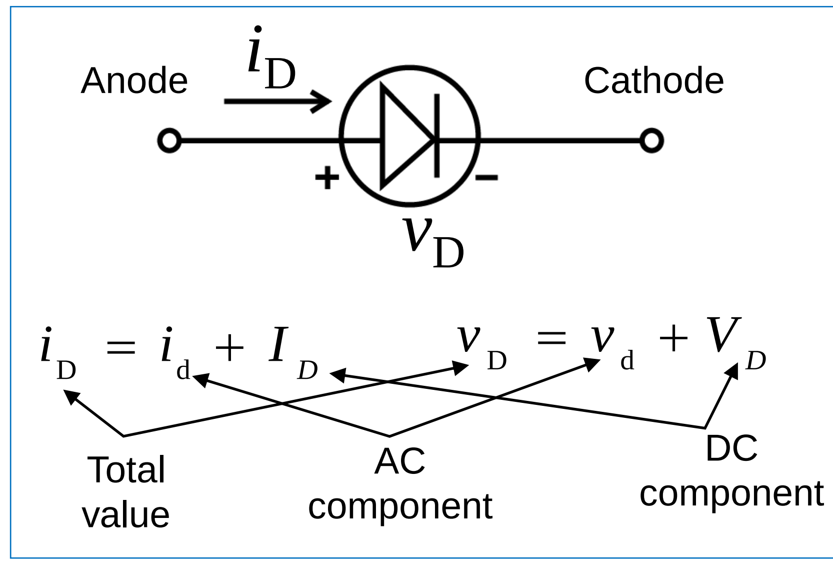


Figure 4. The circuit symbol of a pn junction

Real Diodes

The formation of a pn junction is shown in Figure 5.

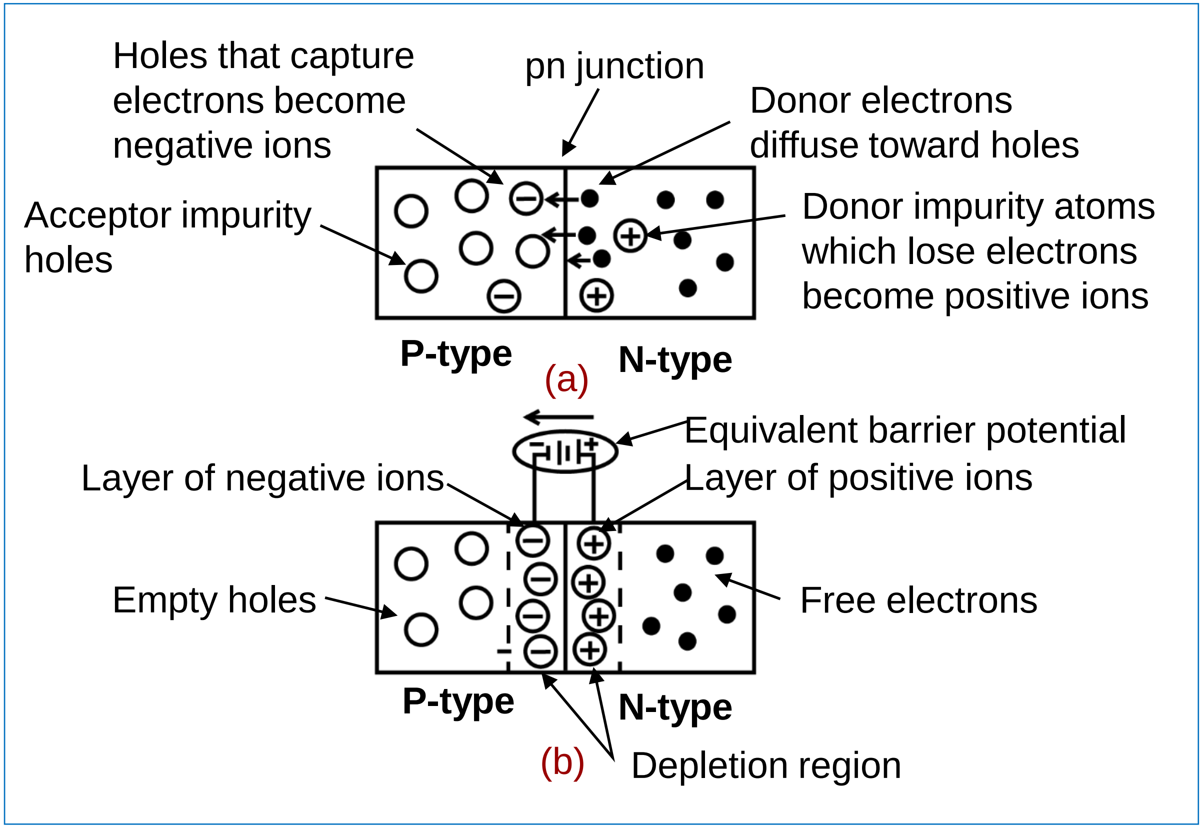


Figure 5. The formation of a pn junction.

Barrier potential:

Germanium (Ge) ≅ 0.2~0.30 V

Silicon (Si) ≅ 0.6~0.70 V

Forward-bias of a PN Junction

Forward-bias is one of the two possible ways to apply an external voltage source to a pn junction.

The details are shown in Figure 6.

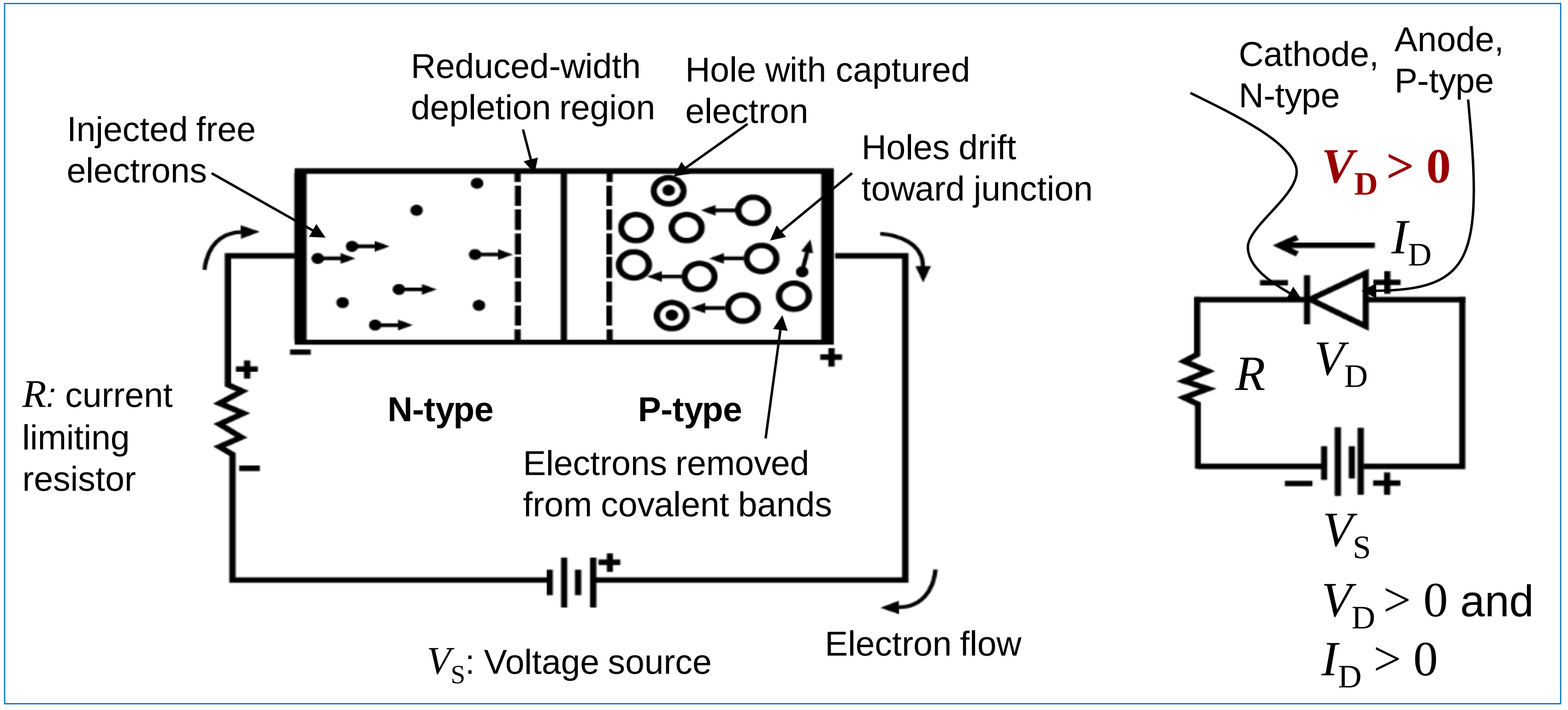


Figure 6. The pn junction with forward-bias.

Forward-bias of a PN Junction

A pn junction is forward-biased by an external voltage source which makes its p-type end more positive than its n-type end.

A forward-biased junction will allow current flow through it.

Reverse-bias of a PN Junction

Under reverse-bias condition, the external voltage source is applied to the pn junction as shown in Figure 7.

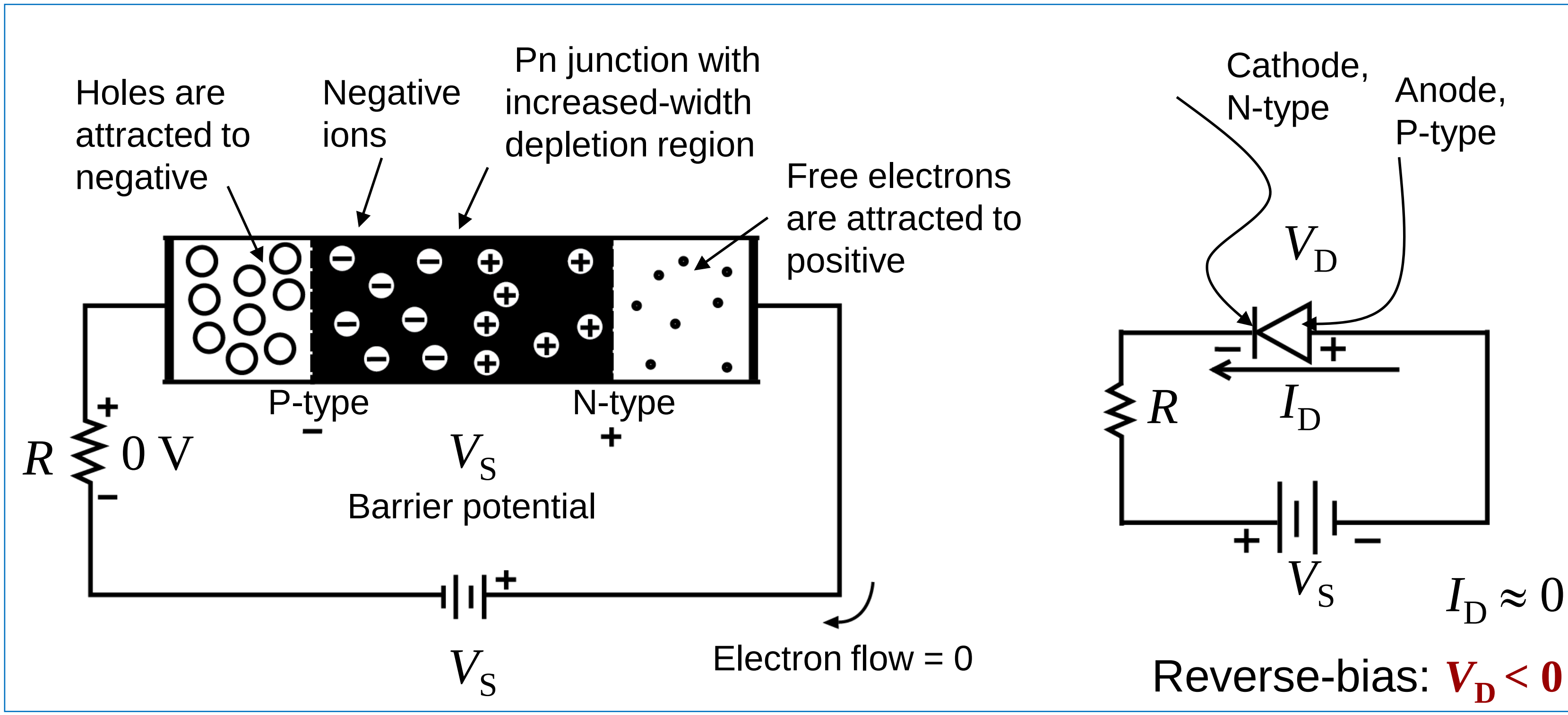


Figure 7. The pn junction with reverse- bias.

Reverse-bias of a PN Junction

- A pn junction is reverse-biased by an external voltage source which makes its p-type end more negative than its n-type end.

- A reverse-biased pn junction will have a current of approximately zero through it.

Terminal Characteristics of Junction Diodes

Figure 8 shows the silicon junction diode *i*-*v* characteristics.

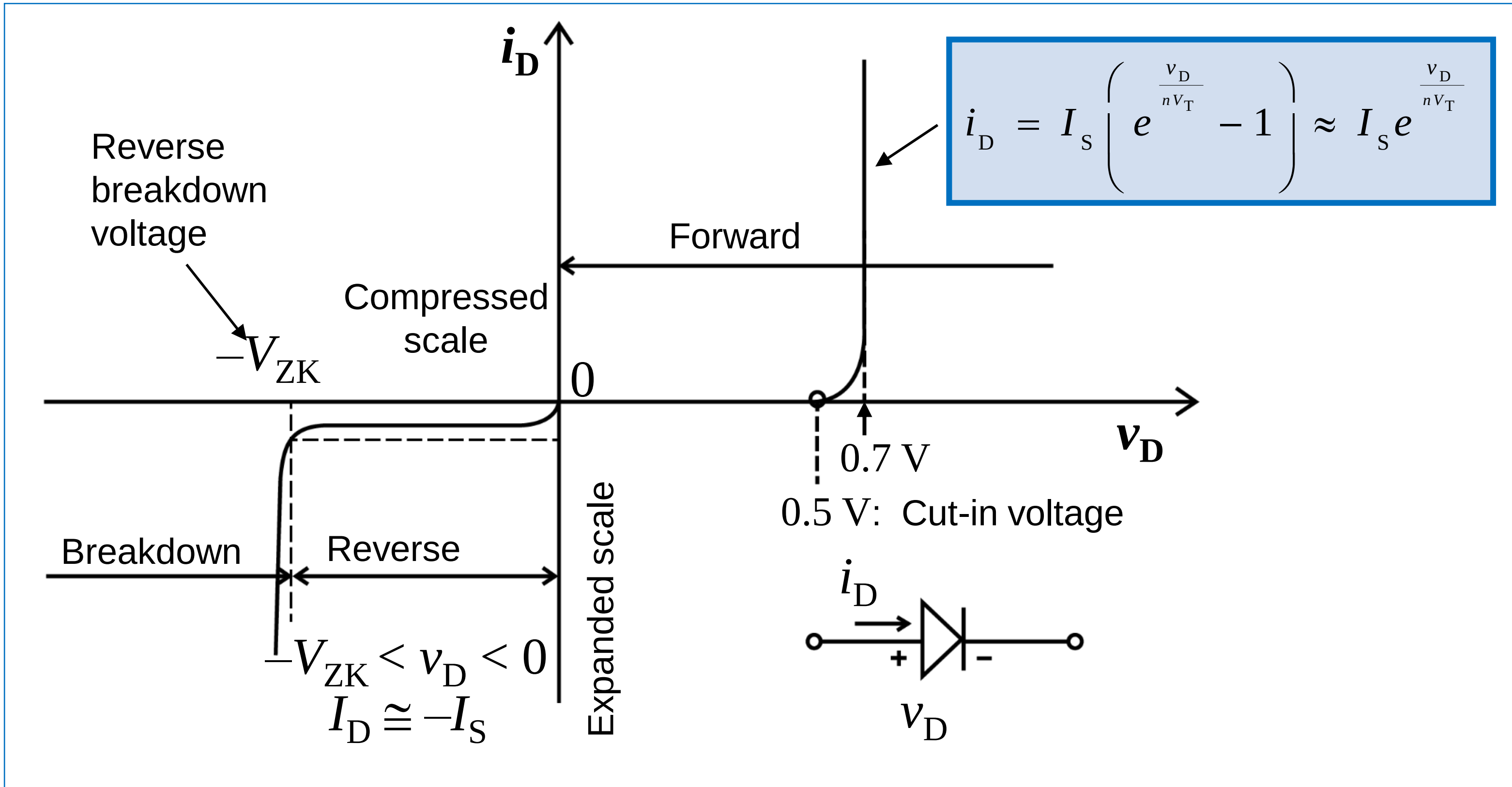


Figure 8. The diode i-v relationship with some scales expanded and others compressed in order to reveal details.

Terminal Characteristics of Junction Diodes

Three Distinct Regions:

- Forward-bias region, $v_D > 0$
- Reverse-bias region, $-V_{ZK} < v_D < 0$
- Breakdown region, $v_D < -V_{ZK}$

For $0 < v_D < 0.5$ V, $I_D \approx 0$

For normal applications, $-V_{ZK} < v_D < \approx 0.70$ V

The Forward-Bias Region

The forward-bias region of operation is entered when terminal voltage $v_D > 0$ and the i-v relationship is described by the Shockley diode equation.

$$\boxed{\begin{aligned} I_D &= I_S\left(e^{\frac{v_D}{nV_T}} - 1\right) \\ &\approx I_S e^{\frac{v_D}{nV_T}} \end{aligned}} \qquad \text{——— (1)}$$

where,

I_D = diode current (A),

I_S = saturation current (A),

- doubles in value for every 10^{o}C rise in temperature
- is of the order of 10^{-17} A for normal diodes

The Forward-Bias Region

(Cont.)

n =1 (emission coefficient), and

V_T = thermal voltage [see equation(2)].

$$V_T = \frac{kT}{q} \quad \text{———} \quad (2)$$

where,

k = Boltzmann's constant, 1.38×10^{-23} J/K

T = absolute temperature (Kelvin)

q = charge on one electron, 1.602×10^{-19} C.

$$I_D = I_S\left(e^{\frac{v_D}{nV_T}} - 1\right)$$

$$\approx I_S e^{\frac{v_D}{nV_T}}$$

At room temperature (27^{o}C),

*$V_T \approx 25$ mV or 26 mV at 27^{o}C .

*(depends on which book is used)

The Forward-Bias Region

For $I_D >> I_S$, equation (1) becomes

$$I_D \cong I_S e^{\frac{v_D}{nV_T}} \text{ ——— } (3)$$

or

$$v_D = nV_T \ln\left(\frac{i_D}{I_S}\right) \text{ ——— } (4)$$

Figure 8 reveals (See slide 19):

- I_D is negligibly small for $v_D < 0.5\ \mathrm{V}$, the cut-in voltage.
- v_D varies within 0.5 to $0.9\ \mathrm{V}$ for a conducting diode.

The Forward-Bias Region

Using equation (4), $v_D = nV_T \ln\left(\frac{i_D}{I_S}\right)$,

1-mA diode: $I_D = 1.0$ mA, $v_D = 0.65$ V

1-A diode: $I_D = 1.0$ A, $v_D = 0.83$ V

Check if you can compute!

However, for simple diode model, assuming $v_D = 0.70$ V, irrespective of the current,

$I_D = 1.0$ mA, $v_D = 0.70$ V;

$I_D = 1.0$ A, $v_D = 0.70$ V.

The Forward-Bias Region

The forward-bias diode i_D-v_D characteristic varies with temperature as shown in Figure 9.

At a given constant I_D, v_D decreases by approximately 2 mV for every 1°C increase in temperature, i.e., the temperature coefficient (TC) is –2 mV/°C.

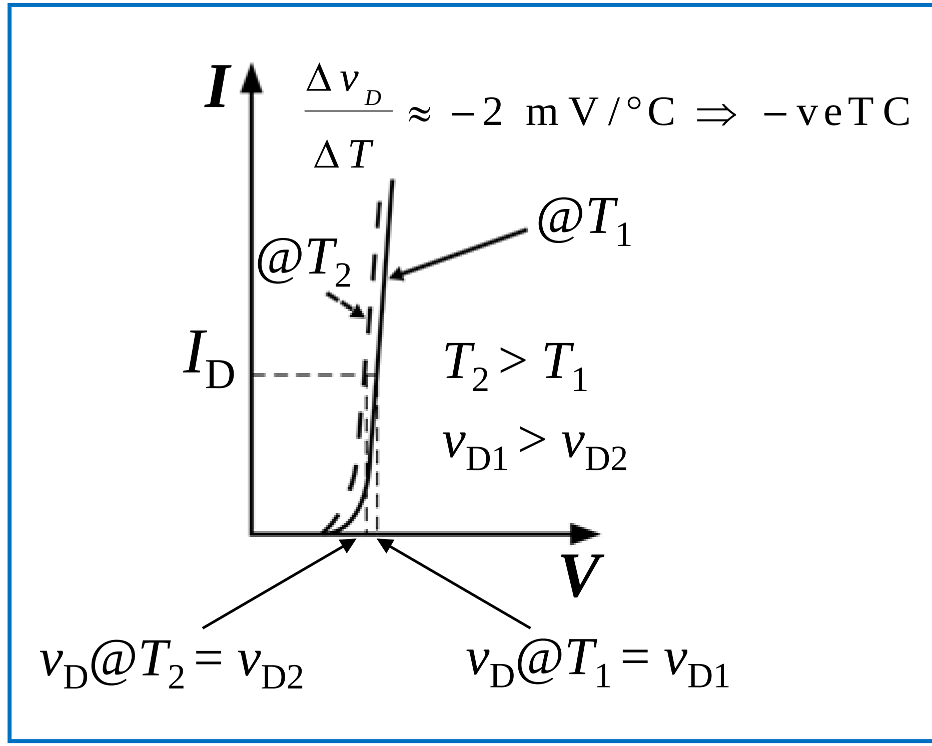


Figure 9. Illustration of the temperature dependence of the diode forward characteristics

This property can be used to build a thermometer.

The Reverse-Bias Region

In this region V_D is negative, but with $v_D > -V_{ZK}$.

If $|v_D| << V_T$, then equation becomes:

$$i_D = I_S\left(e^{\frac{v_D}{nV_T}} - 1\right) \Rightarrow -I_S$$

$$\because \text{ for } v_D << V_T \Rightarrow e^{\frac{v_D}{nV_T}} << 1$$

$$\therefore \quad i_D \cong -I_S \qquad \text{——— (5)}$$

The Breakdown Region

The breakdown region diode operation is achieved when the reverse-bias voltage exceeds a threshold value (breakdown voltage) specific to the particular diode.

This is shown in Figure 8 (as shown in slide 19) and is denoted V_{ZK}.

Analysis of Diode Circuits

Consider the diode circuit shown in Figure 10.

The values for I_D and V_D can be found by solving equations (6) and (7).

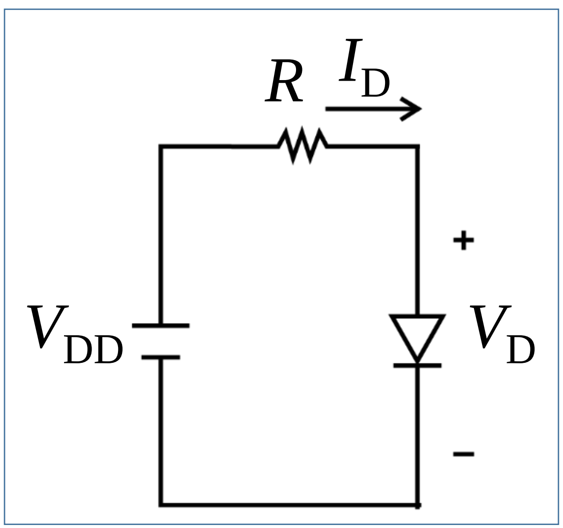


Figure 10. A simple diode circuit.

For $V_{DD} > 0.5\ \mathrm{V}$,

$$I_D = I_S e^{\frac{V_D}{nV_T}} \qquad (6)$$

By KVL,

$$I_D = \frac{V_{DD} - V_D}{R} \qquad (7)$$

Equations (6) and (7) give:

I_D, V_D

Analysis of Diode Circuits

Graphical Analysis

Graphical analysis is done by plotting Equations (6) and (7) on the *i*-*v* plane as depicted in Figure 11.

The straight line represents Equation (7) and is known as load line.

The intersection point of load line and diode characteristic is the operating point Q of the circuit (Q stands for Quiescent).

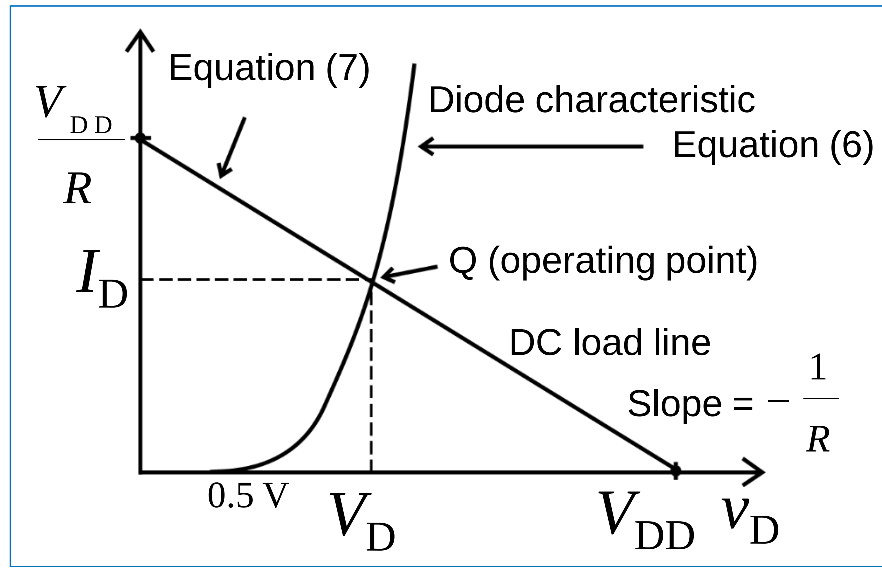
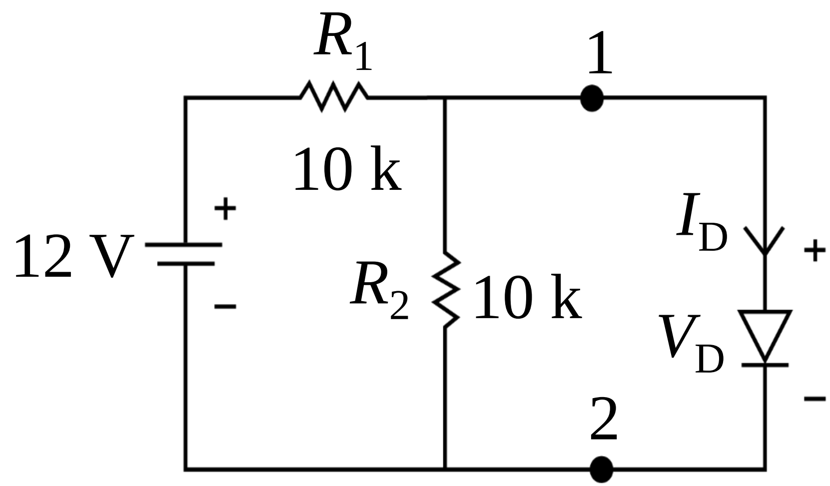


Figure 11. Graphical analysis of the circuit in Figure 10.

Analysis of Diode Circuits

Iterative Solution

Solving diode circuit by iteration method:



Given for the diode D: $I_S = 10\ \text{nA};\ n = 2$

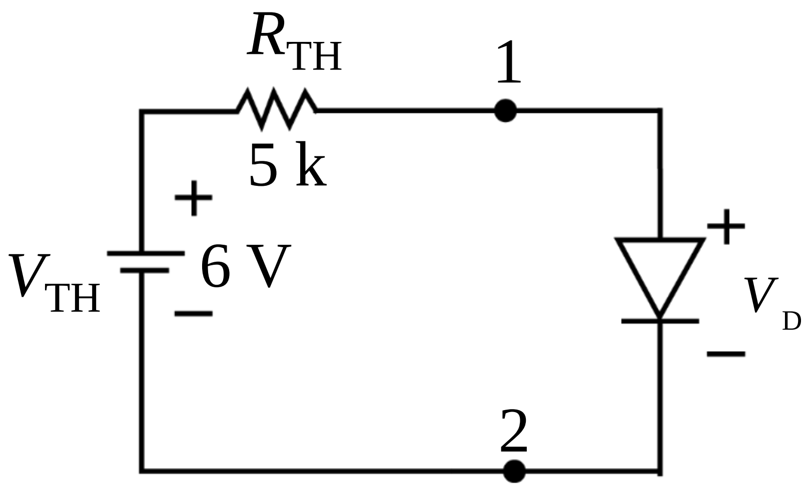
$$\therefore\ I_D = I_S e^{\frac{V_D}{2V_T}} \quad \text{or} \quad V_D = 2V_T \ln \frac{I_D}{I_S}$$

Analysis of Diode Circuits

Iterative Solution

Solution:

Step 1: Thevenin equivalent circuit seen by V_D



$$R_{TH} = R_1 // R_2$$
$$= 5.0 \text{ k}$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2} \right) V_S$$
$$= \frac{10}{20} 12$$
$$= 6.0 \ V$$

Loadline eq'n: $I_D = \dfrac{V_{TH} - V_D}{R_{TH}}$

Analysis of Diode Circuits

Iterative Solution

Solution (Cont.):

Step 2: Try $V_D = 0.70$ V, then

$$I_D \cong \frac{V_{TH} - 0.70V}{R_{TH}} \cong 1.06 \text{ mA}$$

Step 3: $V_D \cong 2 \times 0.026 \ln\left(\frac{1.06 \text{ mA}}{10 \text{ nA}}\right) = 0.602 \text{ V}$

Analysis of Diode Circuits

Iterative Solution

Solution (Cont.):

Step 4: $$I_D \cong \frac{6-0.602}{5} = 1.08 \text{ mA}$$

Step 5: $$V_D \cong 2 \times 0.026 \ln\left(\frac{1.08 \text{ mA}}{10 \text{ nA}}\right) = 0.603 \text{ V}$$

Step 6: $$I_D \cong \frac{6-0.603}{5} = 1.079 \text{ mA}$$

Analysis of Diode Circuits

Iterative Solution

Solution (Cont.):

Step 7: $V_D \cong 0.026 \ln\left(\dfrac{1.079\ \text{mA}}{10\ \text{nA}}\right) = 0.603\ \text{V}$

$$I_D = \frac{V_{TH} - V_D}{5.0} \qquad 1.06^{(2)} \quad 1.08^{(4)} \quad 1.079^{(6)} \quad 1.079^{(8)}\ \text{mA}$$

$$V_D = 2V_T \ln\left(\frac{I_D}{I_S}\right) \qquad 0.70^{(1)} \quad 0.602^{(3)} \quad 0.603^{(5)} \quad 0.603^{(7)}\ \text{V}$$

Initial guess value for V_D

Q-point: $I_D = 1.079$ mA, $V_D = 0.603$ V

Analysis of Small-signal Diode Circuits

Consider the circuit shown in the Figure 12(a).

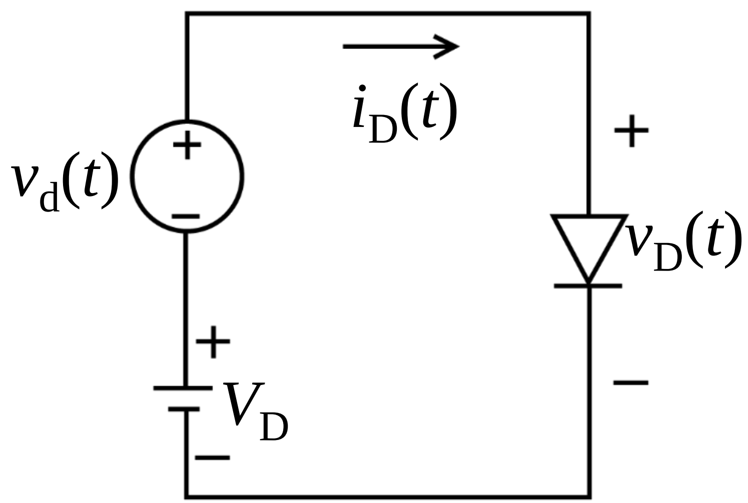


Figure 12(a). Diode with AC and DC voltages.

$$v_D(t) = V_D + v_d(t)$$

$$i_D(t) \cong I_S e^{\frac{v_D}{nV_T}}$$

$$= I_S e^{\frac{V_D + v_d(t)}{nV_T}}$$

$$= I_S e^{\frac{V_D}{nV_T}} e^{\frac{v_d(t)}{nV_T}}$$

$$= I_D e^{\frac{v_d(t)}{nV_T}}$$

Analysis of Small-signal Diode Circuits

$$e^{x} = 1 + x + \frac{x^{2}}{2!} + \frac{x^{3}}{3!} + \ldots$$

$$x \ll 1 \Rightarrow e^{x} = 1 + x$$

If $x = \dfrac{v_d}{nV_T}$, For $\dfrac{v_d}{nV_T} \ll 1$,

$$e^{\frac{v_d}{nV_T}} \cong 1 + \frac{v_d}{nV_T}$$

$$\therefore \quad i_{\mathrm{D}}(t) = I_{\mathrm{D}} e^{\frac{v_{\mathrm{d}}(t)}{nV_{\mathrm{T}}}}$$

$$\cong I_{\mathrm{D}}\left(1 + \frac{v_{\mathrm{d}}(t)}{nV_{\mathrm{T}}}\right)$$

$$i_{\mathrm{D}}(t) \cong I_{\mathrm{D}} + \frac{I_{\mathrm{D}}}{nV_{\mathrm{T}}} v_{\mathrm{d}}(t)$$

$$= I_{\mathrm{D}} + g_{\mathrm{d}} v_{\mathrm{d}}(t)$$

$$= I_{\mathrm{D}} + i_{\mathrm{d}}(t)$$

where $g_{\mathrm{d}} = \dfrac{I_{\mathrm{D}}}{nV_{\mathrm{T}}}$.

Analysis of Small-signal Diode Circuits

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g_d is the small-signal conductance for the diode and
$i_d(t) = g_d\, v_d(t)$.

$i_d(t)$ is the small-signal diode current due to the small-signal voltage, $v_d(t)$, across the diode.

The magnitude of

$v_d(t) \ll nV_T$.

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \ldots$$

$$\frac{x^2}{2!} \ll x \Rightarrow \frac{x}{2} \ll 1 \Rightarrow x \ll 2$$

If $x = \dfrac{v_d}{nV_T} \Rightarrow \dfrac{v_d}{nV_T} \ll 2$

$$\Rightarrow v_d \ll 2nV_T$$

If $n = 1 \Rightarrow v_d \ll 2nV_T$

$$\Rightarrow v_d \ll 2 \times 26 \text{ mV}$$

$$v_d < 5 \text{ mV}$$

Analysis of Small-signal Diode Circuits

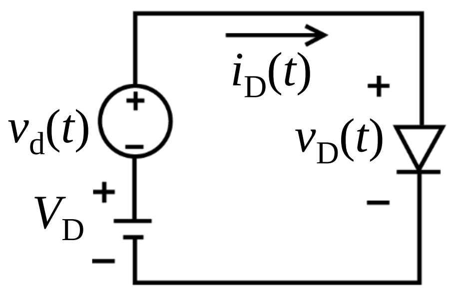


Figure 12(a). Diode with AC and DC voltages.

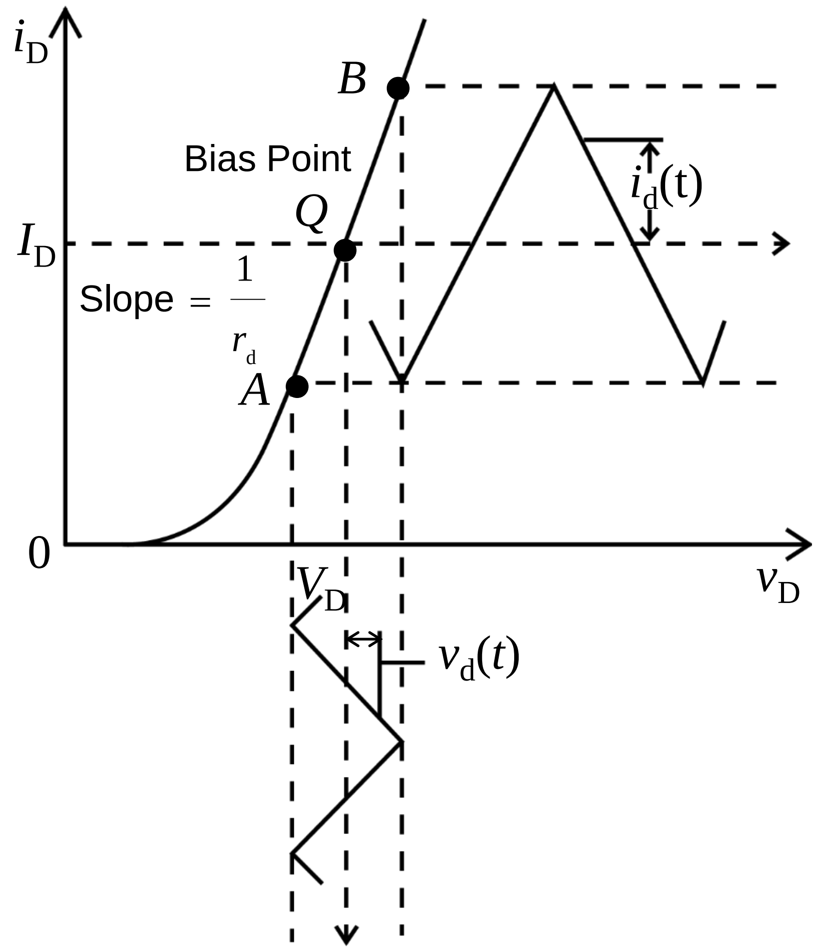


Figure 12(b). Illustration of where the AC signal is riding on the DC Q-point.

Diode Circuit Analysis

Application of Linear Superposition Principle

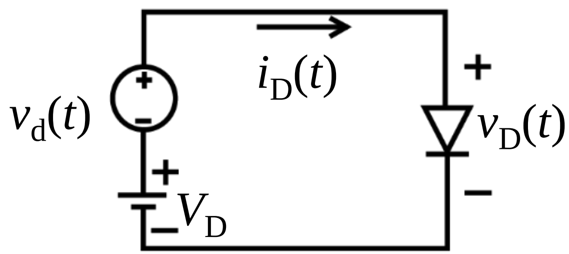
This method is valid if

$v_d(t) \ll V_T$

$(v_d(t) < 5\ \mathrm{mV})$

$$v_D(t) = V_D + v_d(t)$$

$$i_D(t) = I_D + i_d(t)$$



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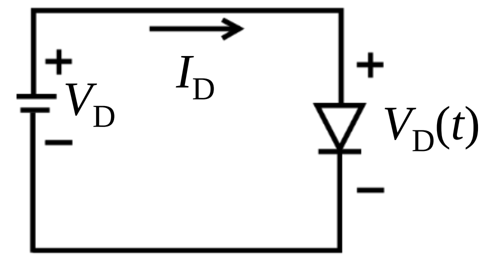
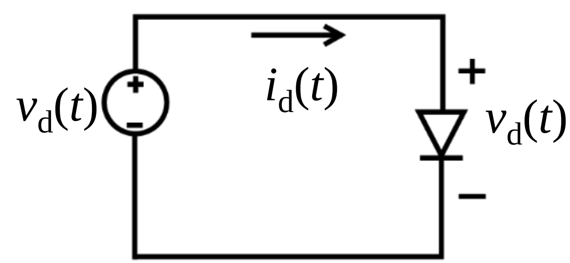


(a)

$+$



(b)

Diode Circuit Analysis

Application of Linear Superposition Principle

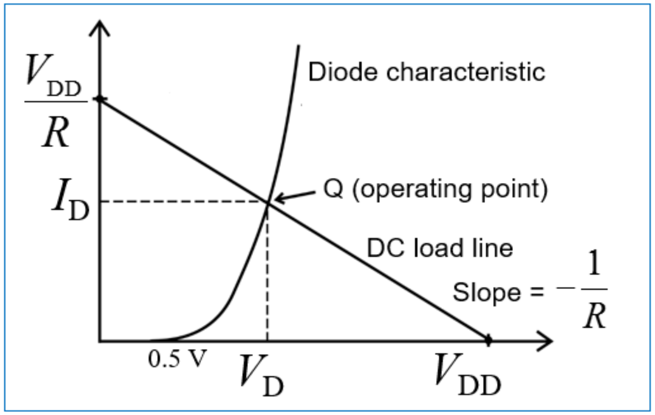
(i) The DC values for V_D and I_D can be found from the diode's forward i_D-v_D curve described by the equation

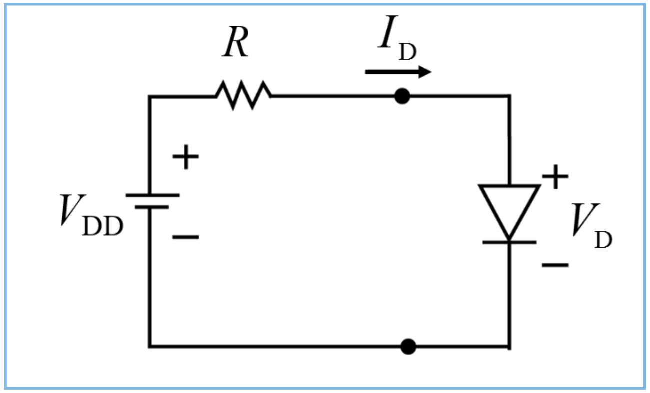
$$i_D \cong I_S e^{\frac{v_D}{nV_T}} \quad \text{or} \quad v_D \cong nV_T \ln\left(\frac{i_D}{I_S}\right)$$

and the load line equation

$$I_D = \frac{V_{DD} - V_D}{R}$$

The DC values, I_D and V_D, are the coordinates of the Q-point.





Diode Circuit Analysis

Application of Linear Superposition Principle

(ii) The AC values for $i_d(t)$ and $v_d(t)$ can be determined if $i_d(t)$ varies slightly around the Q-point (Figure 12-b in slide 38), i.e., within the portion AB of diode's i_D-v_D curve.

This portion of i_D-v_D curve approximates a straight line. Thus, $i_d(t)$ and $v_d(t)$, are linearly related.

The slope or the small-signal conductance of the i_D-v_D curve around the Q-point is constant.

Diode Circuit Analysis

Application of Linear Superposition Principle

From $i_D \cong I_S e^{\frac{v_D}{nV_T}}$, $\dfrac{\Delta i_D}{\Delta v_D} = \dfrac{I_S}{nV_T} e^{\frac{v_D}{nV_T}}$.

$$\therefore\ g_d \equiv \left.\frac{\Delta i_D}{\Delta v_D}\right|_{v_D = V_D}$$

$$g_d = \frac{1}{nV_T} I_S e^{\frac{V_D}{nV_T}}$$

$$g_d = \frac{I_D}{nV_T}$$

$$\therefore\ i_d(t) = g_d v_d(t)$$

- small-signal conductance of the diode at the Q-point
- g_d = slope of the i_D-v_D curve at the Q-point
- g_d is proportional to the DC current flowing through the diode

Diode Circuit Analysis

Application of Linear Superposition Principle

e.g.

Given: $n = 1$, $V_T = 0.026$ V or 26 mV, and $I_D = 1$ mA

$$g_d = \frac{1 \times 10^{-3}}{1 \times 0.026}$$

$$= 0.0385 \ \frac{\mathrm{A}}{\mathrm{V}}$$

$$= 38.5 \text{ mS or m℧} \qquad (\text{S: siemens} = ℧\text{: mho})$$

Diode Circuit Analysis

Application of Linear Superposition

e.g. (Cont.)

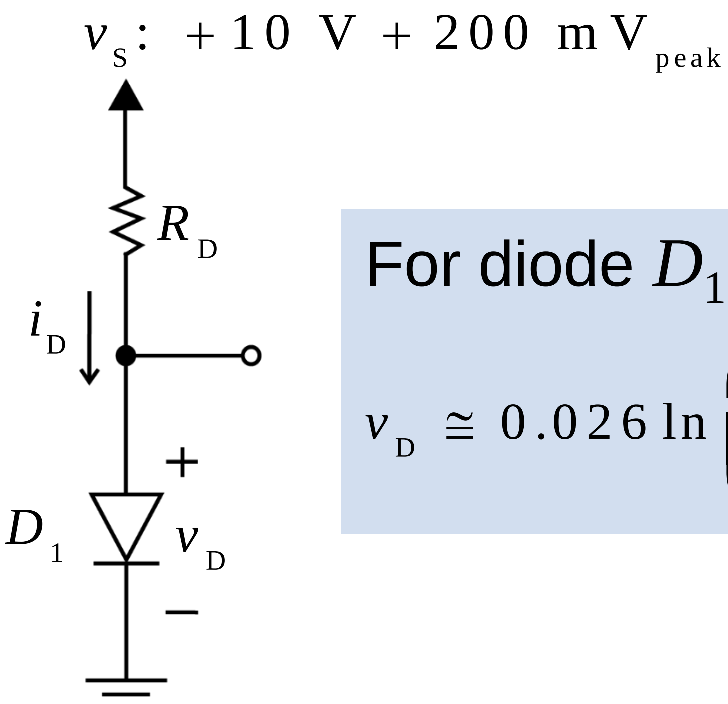
The small-signal resistance or incremental resistance, of a diode at Q-point is the reciprocal of the small-signal conductance.

$$\boxed{r_d \equiv \frac{1}{g_d} = \frac{nV_T}{I_D}}$$

In terms of r_d,

$$\boxed{v_d(t) = i_d(t)\, r_d}$$

Diode Circuit Analysis: Example

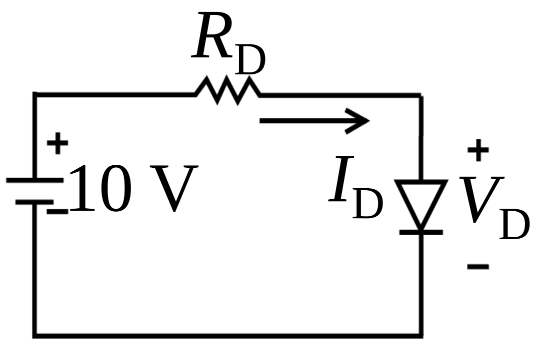


For diode D_1, $I_S = 10^{-14}$ A and $n = 1$.

$v_D \cong 0.026 \ln\left(\frac{i_D}{I_S}\right)$. Find v_D and i_D.

Analysis of Small-signal Diode Circuits

1. DC Analysis



$$I_D = \frac{10 - V_D}{10} \text{ mA}$$

$$I_D = \frac{10 - V_D}{10}$$

$$V_D = 0.026 \ln\left(\frac{I_D}{I_S}\right)$$

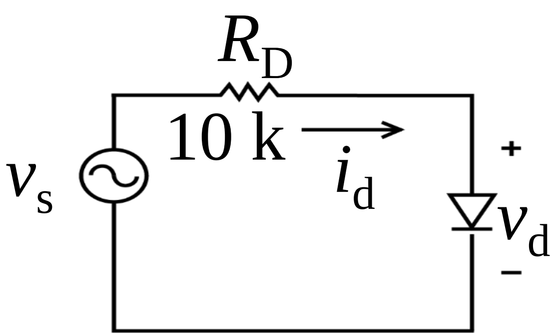
$0.932^{(2)}$ $0.934^{(4)}$ $0.934^{(6)}$ mA

$0.70^{(1)}$ $0.657^{(3)}$ $0.657^{(5)}$ V

Q-point for the diode circuit: $I_D = 0.934 \text{ mA}$, $V_D = 0.657 \text{ V}$

Analysis of Small-signal Diode Circuits

2. <u>AC Analysis</u>



$$i_d = i_D - I_D$$

$$v_d = v_D - V_D$$

The small-signal resistance for the diode at the Q-point determined in (1) is

$$r_d = \frac{V_T}{I_D} = \frac{26\ \mathrm{mV}}{0.934\ \mathrm{mA}} = 27.84\ \Omega$$

Analysis of Small-signal Diode Circuits

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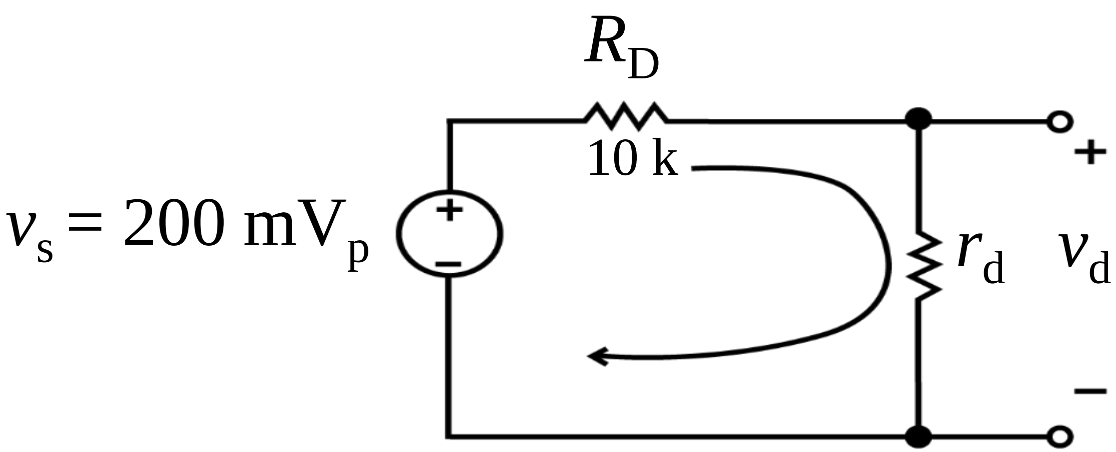
2. AC Analysis (Cont.)



$$\therefore\ v_d = \left(\frac{r_d}{r_d + R_D}\right) v_s = \left(\frac{27.84}{10{,}000 + 27.84}\right)(200\ \text{mV})$$

$$= 0.555\ \text{mV}_P$$

Analysis of Small-signal Diode Circuits

2. AC Analysis (Cont.)

$$i_d = \frac{v_d}{r_d} = 0.020 \text{ mA}_p$$

$$\boxed{\begin{aligned} \therefore\ v_D &= V_D + v_d = (657 + 0.555 \sin\omega t) \text{ mV} \\ i_D &= I_D + i_d = (0.934 + 0.020 \sin\omega t) \text{ mA} \end{aligned}}$$

Diode Rectifiers

A **rectifier** is a device that permits current to flow through it in one direction only.

The half-wave rectifier circuit using a diode is shown in Figure 13.

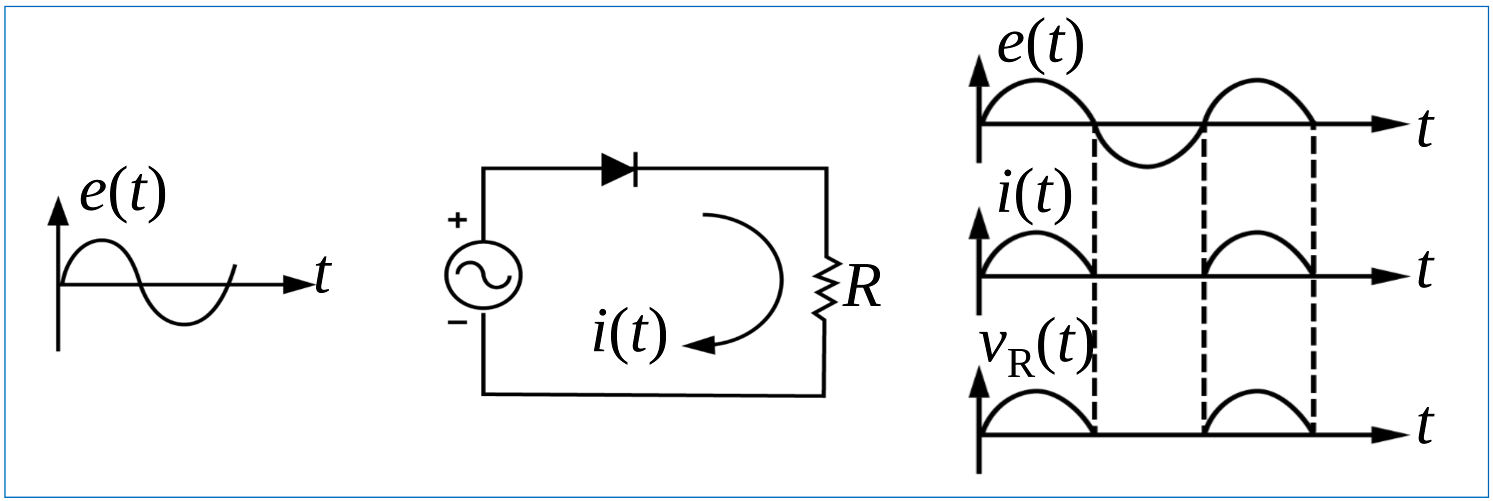


Figure 13. The diode used as a rectifier.

Current flows only during the positive half-cycle of the point.

Elementary DC Power Supplies

- Most practical electronic circuits require a DC voltage source that produces and maintains a constant voltage.
- The pulsating half-sine waves must be converted to a steady DC level which can be done by filtering the waveform

The purpose of filtering the waveform for a DC power is to reject all AC components

Elementary DC Power Supplies

- The process of filtering the waveform can be done by connecting a capacitor directly across the output of a half-wave rectifier.
- The AC components will "see" a low-impedance path to ground and will not therefore appear in the output.

Elementary DC Power Supplies

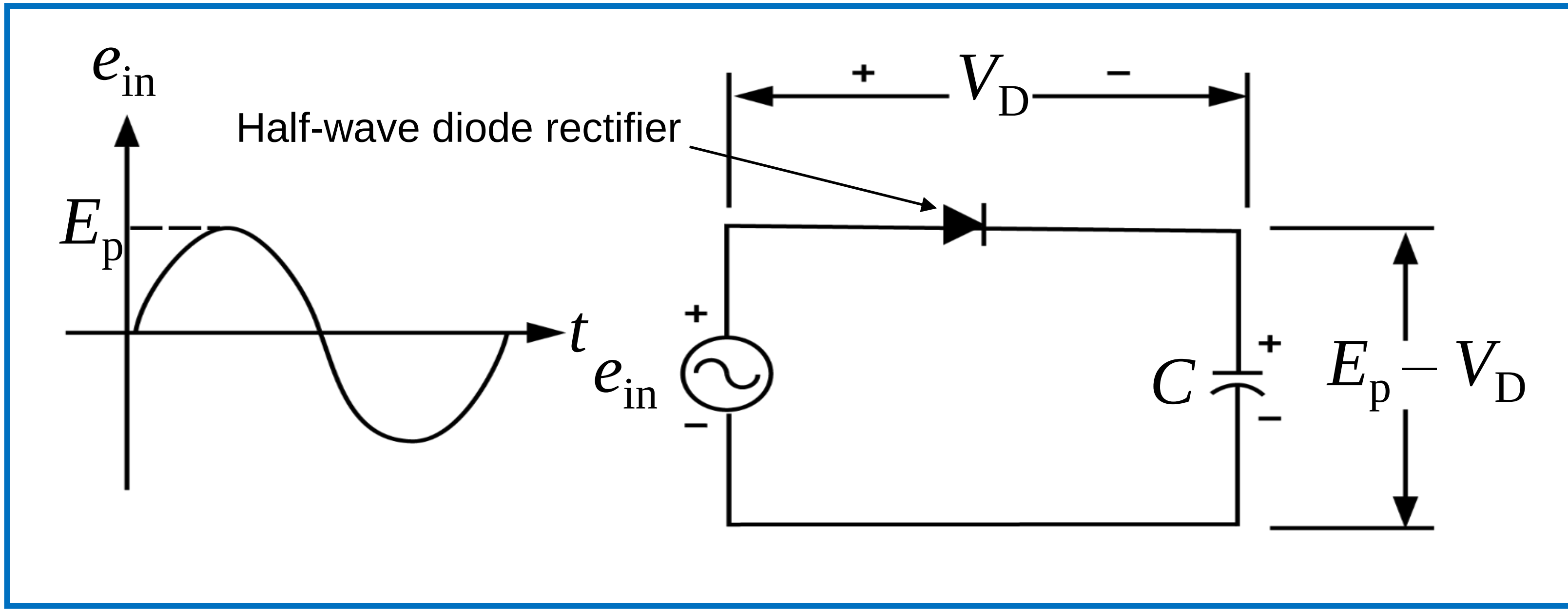


Figure 14. Filter capacitor C effectively removes the AC components from the half-wave-rectified waveform.

Elementary DC Power Supplies

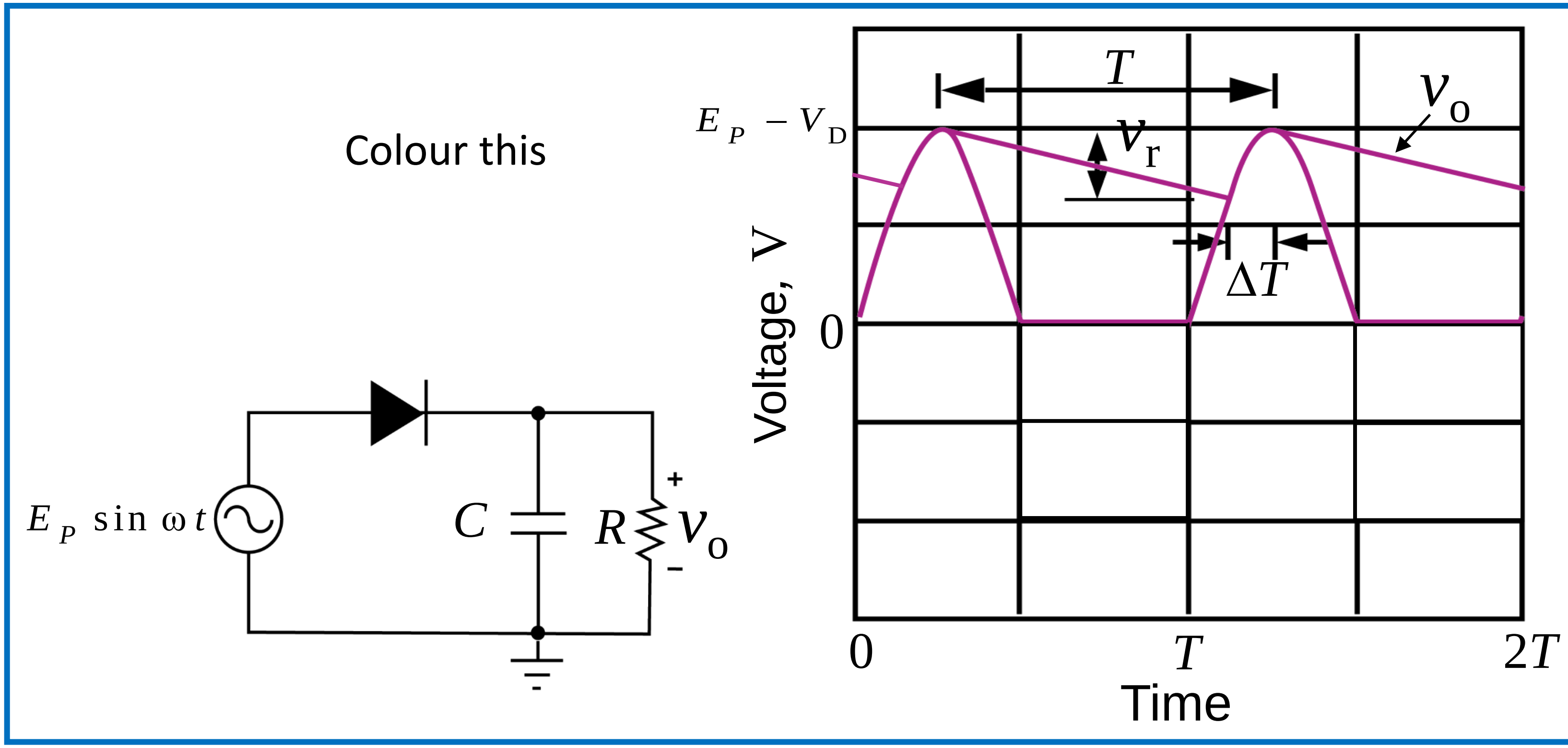


Figure 15. When load resistance R is connected across the filter capacitor, the capacitor charges and discharges, creating a load voltage that has a ripple voltage superimposed on a DC level.

Elementary DC Power Supplies

A full-wave bridge rectifier is shown in Figure 16.

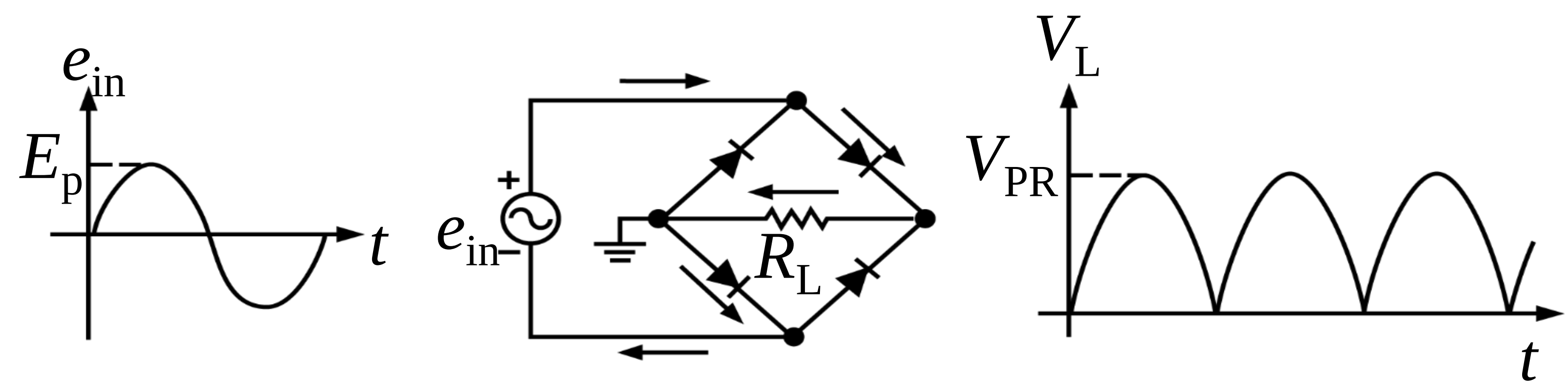


Figure 16. The full-wave bridge rectifier and output waveform.

The arrows show the direction of current flow when e_{in} is positive.

Elementary DC Power Supplies

Figure 17 demonstrates the current flow in the full-wave bridge rectifier.

The peak rectified voltage across R_L is $V_{PR} = E_P - 1.4\text{V}$.

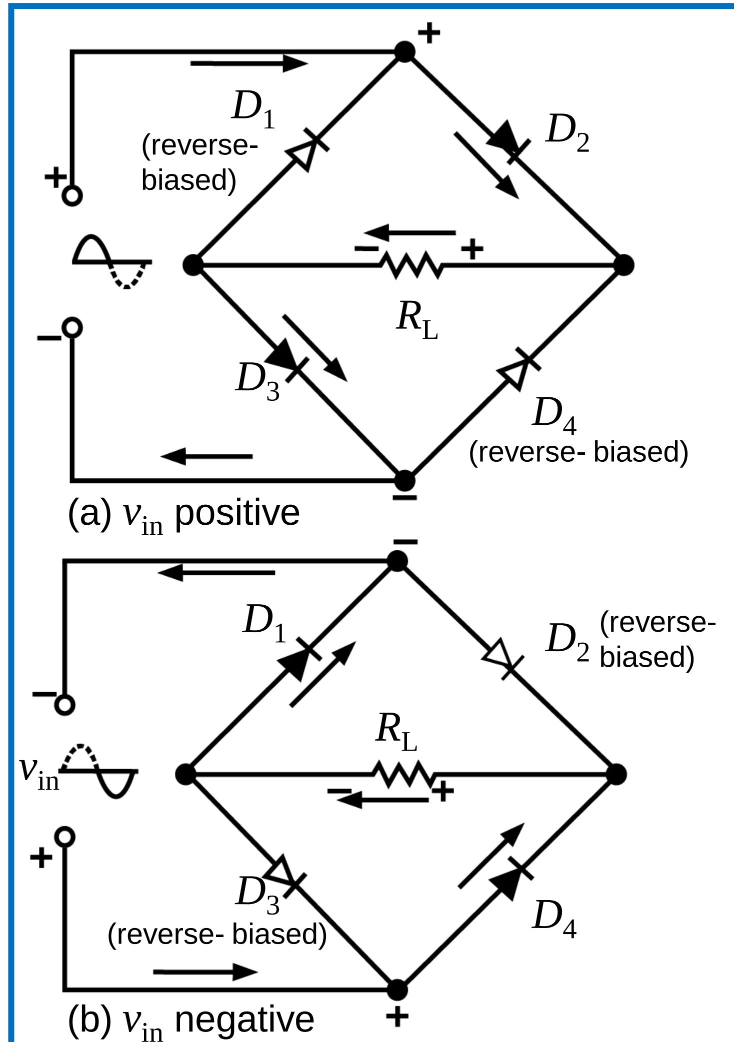


Figure 17. Current flow in the full-wave bridge rectifier.

Elementary DC Power Supplies

The full-wave rectified waveform can be filtered by connecting a capacitor in parallel with load R_L, as shown in Figure 18.

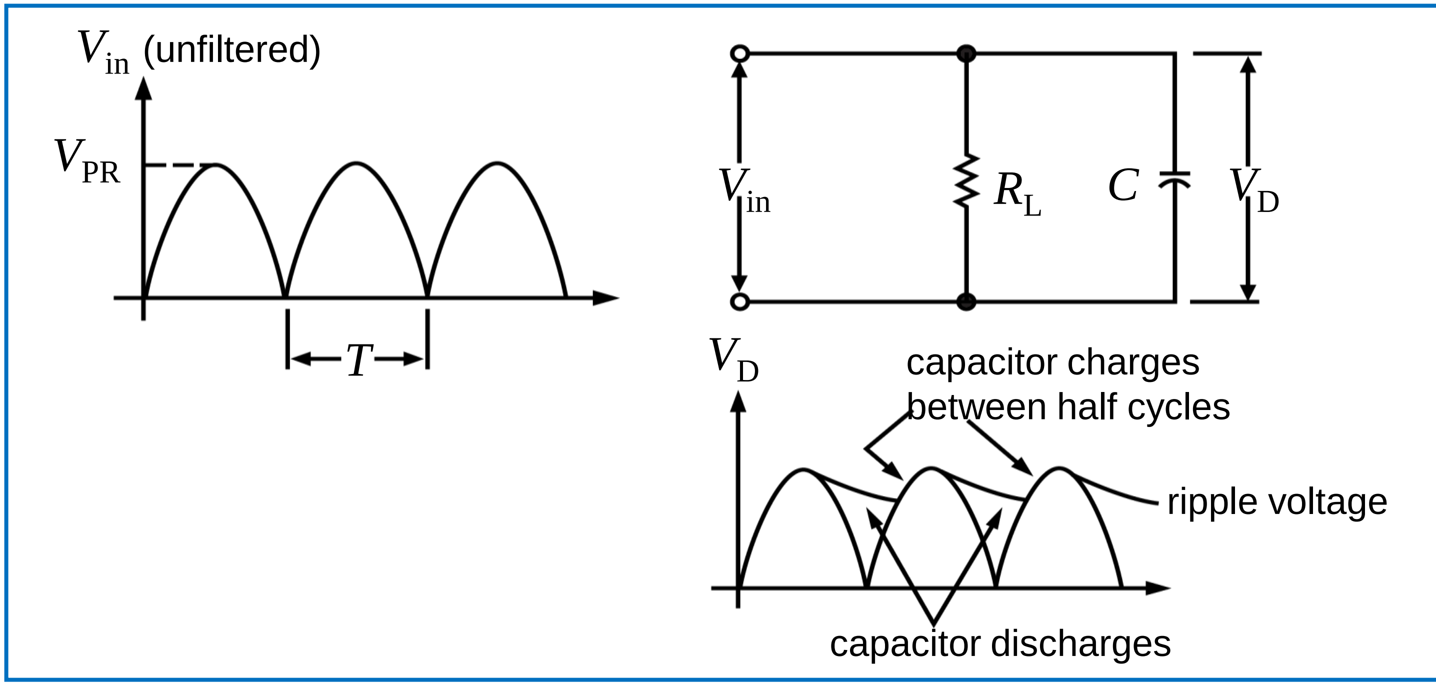


Figure 18. The ripple voltage in the filtered output full-wave rectifier is smaller than in the half-wave case because the capacitor recharges at shorter intervals: T = period of the full-wave rectified waveform (one half the period of the rectified sine wave).

Absolute Value Circuit

The figure below shows the schematic and block diagrams of the commonly used signal wave rectifier circuit.

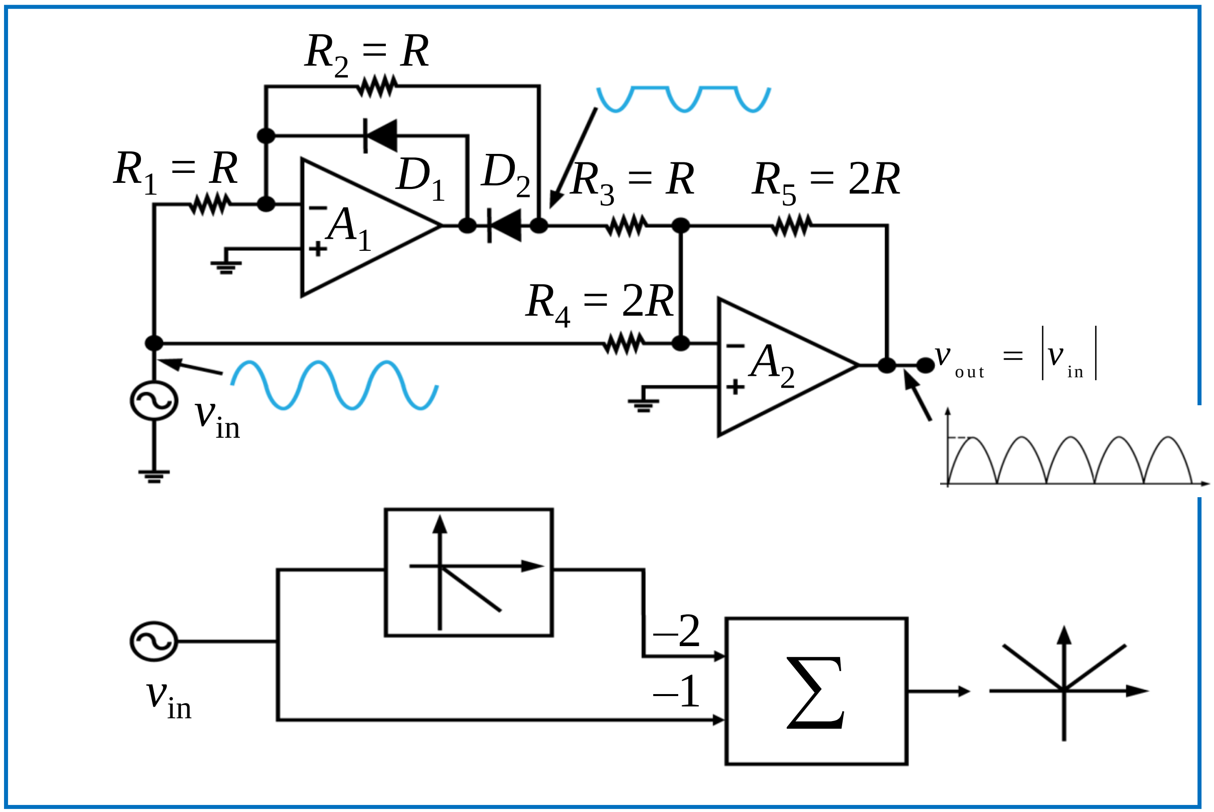


Figure 19. Schematic and block diagrams of the commonly used signal wave rectifier circuit.

Absolute Value Circuit

- When the input signal is positive the output A1 is negative, so D1 is reverse-biased.
- D2 is forward-biased, closing the feedback to loop around A1 through R2 and forming an inverting amplifier.
- A2 sums the output of A1 times a gain of –2 with the input signal times a gain of –1, leaving a net gain of +1.
- When the input signal is negative, D1 is forward-biased, closing the feedback loop around A1.

Absolute Value Circuit

- D2 is reversed-biased and does not conduct.
- A2 inverts the input signal, resulting in a positive output.
- The output of A2 is a positive voltage that represents the absolute value of the input, whether positive or negative.