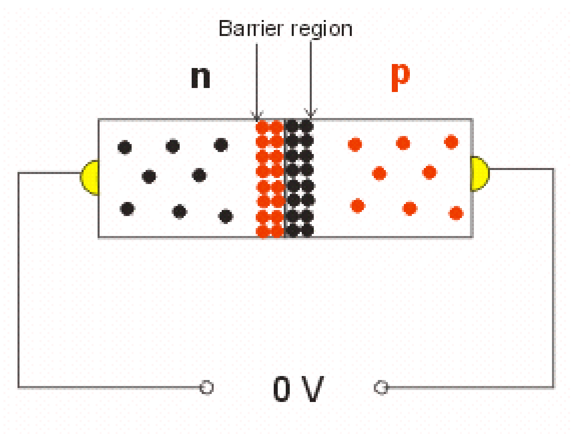
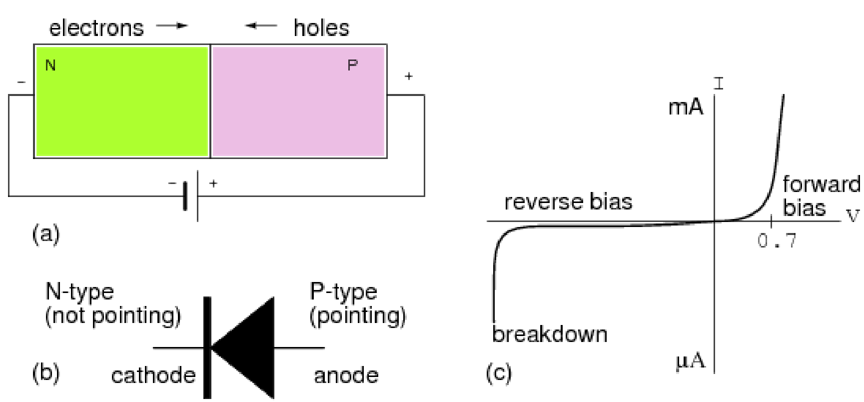
Introduction to Diodes

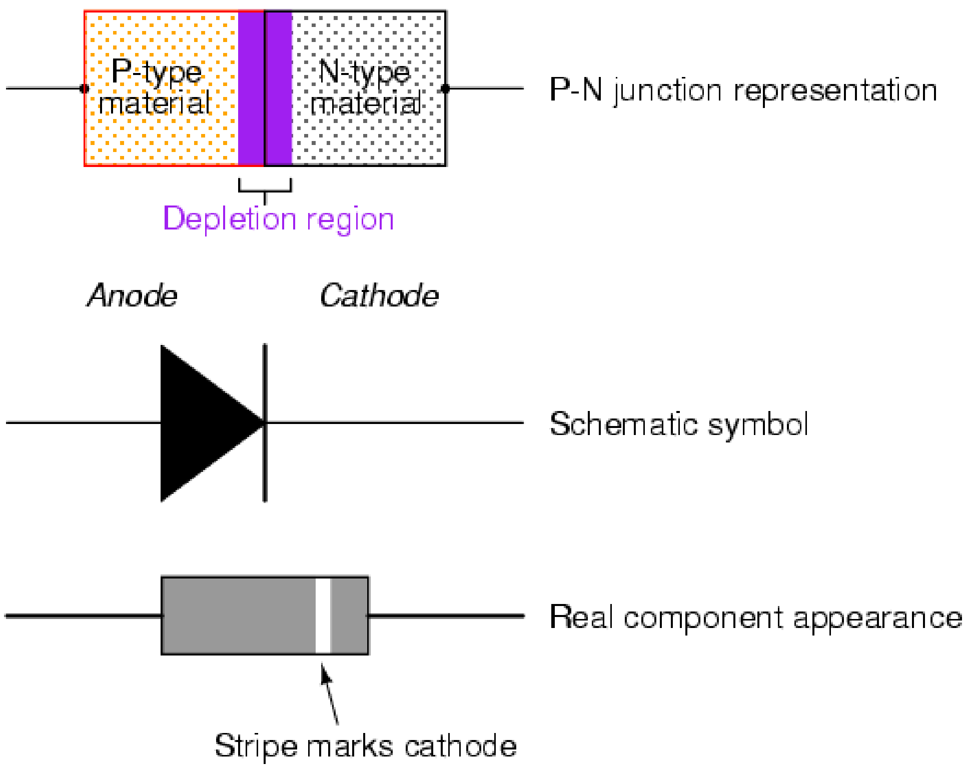


Diode with no bias

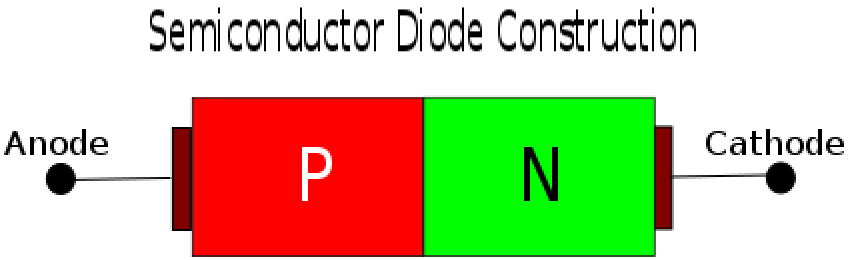


Diode

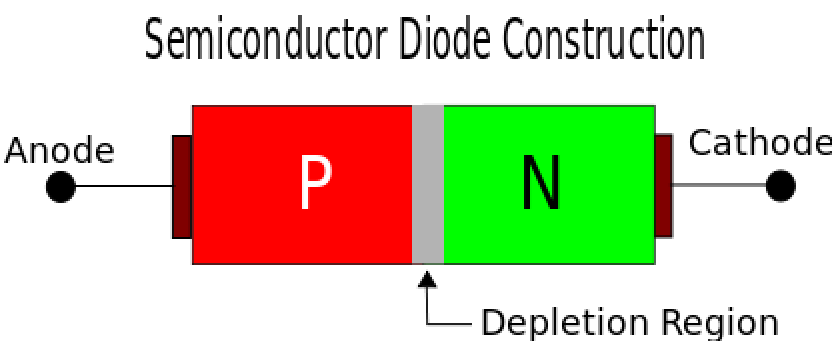
Diodes are electronic devices created by bringing together a *p*-type and *n*-type region within the same semiconductor lattice.



Diode Construction



A diode is formed by joining two equivalently doped P-Type and N-Type semiconductor. The P-Type semiconductor has excess holes and is of positive charge. The N-Type semiconductor has excess electrons.



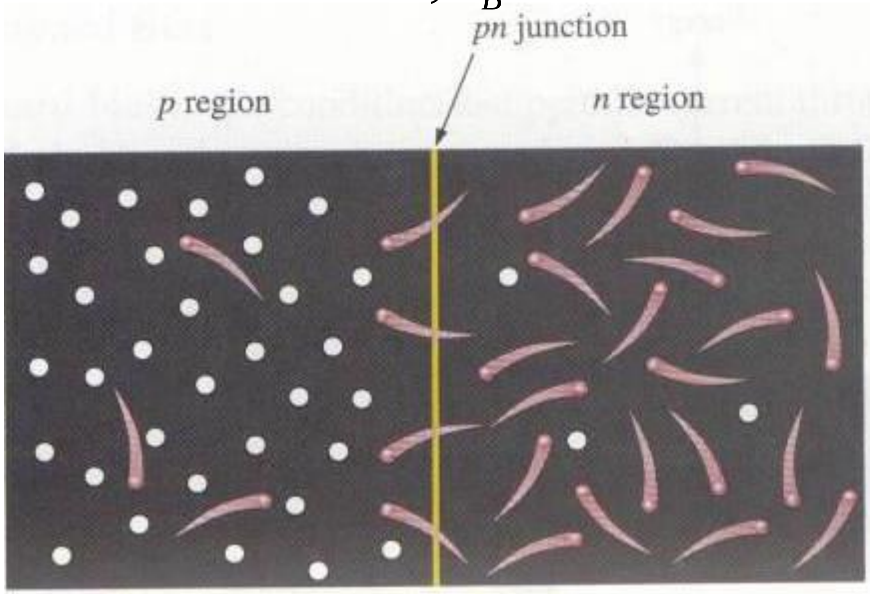
At the junction, the holes in the P-Type attract electrons in the N-Type material. Hence the electron diffuses and occupies the holes in the P-Type material. Causing a small region of the N-type near the junction to loose electrons and behaves like intrinsic semiconductor material, in the P-type a small region gets filled up by holes and behaves like a intrinsic semiconductor.
This depletion region becomes an insulating layer.

The PN-Junction

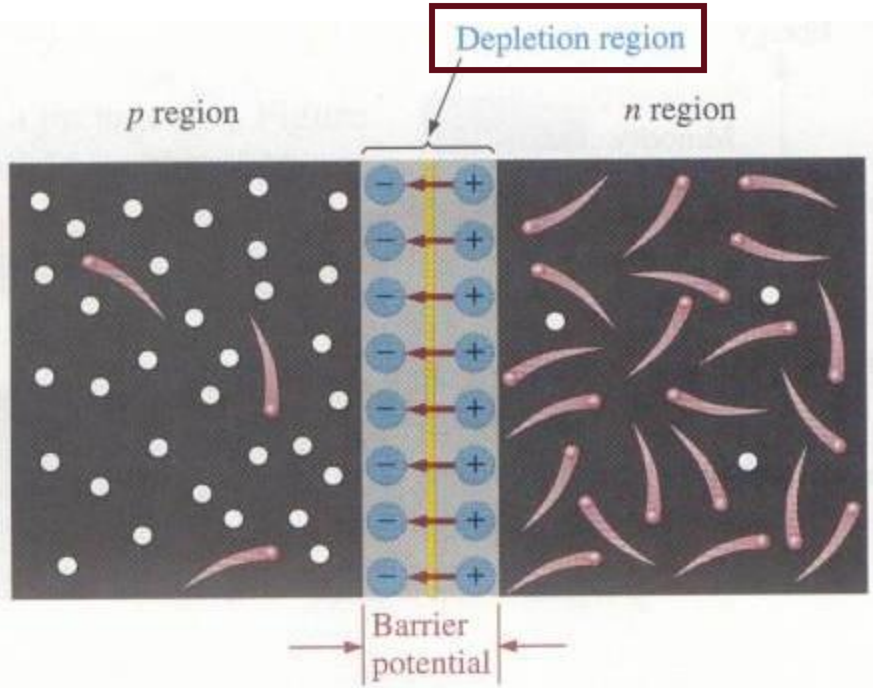
The interface in-between p-type and n-type material is called as *pn-junction*.

$The\ barrier\ potential\ V_B \cong 0.6-0.7V\ for\ Si\ and\ 0.3V\ for\ Ge$

$at\ 300K:\ as\ T\uparrow, V_B\downarrow.$

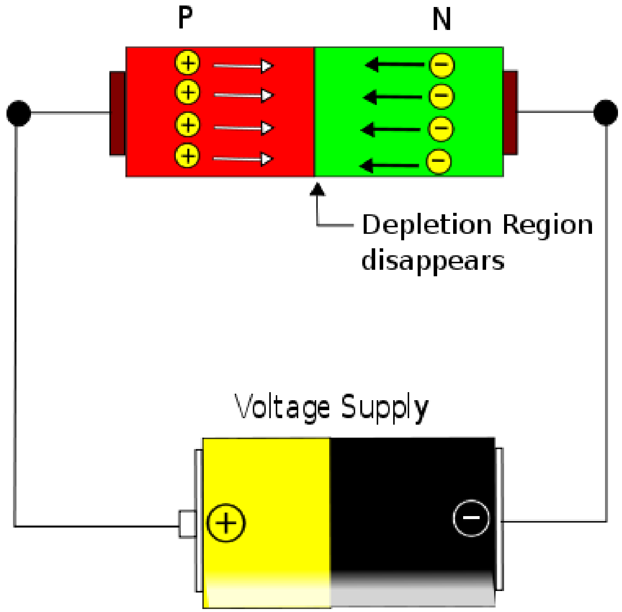


(a) At the instant of junction formation, free electrons in the *n* region near the *pn* junction begin to diffuse across the junction and fall into holes near the junction in the *p* region.



(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion.

Forward Bias



In forward bias the P-Region of the diode is connected with the positive terminal of the battery and N-region is connected with the negative region.

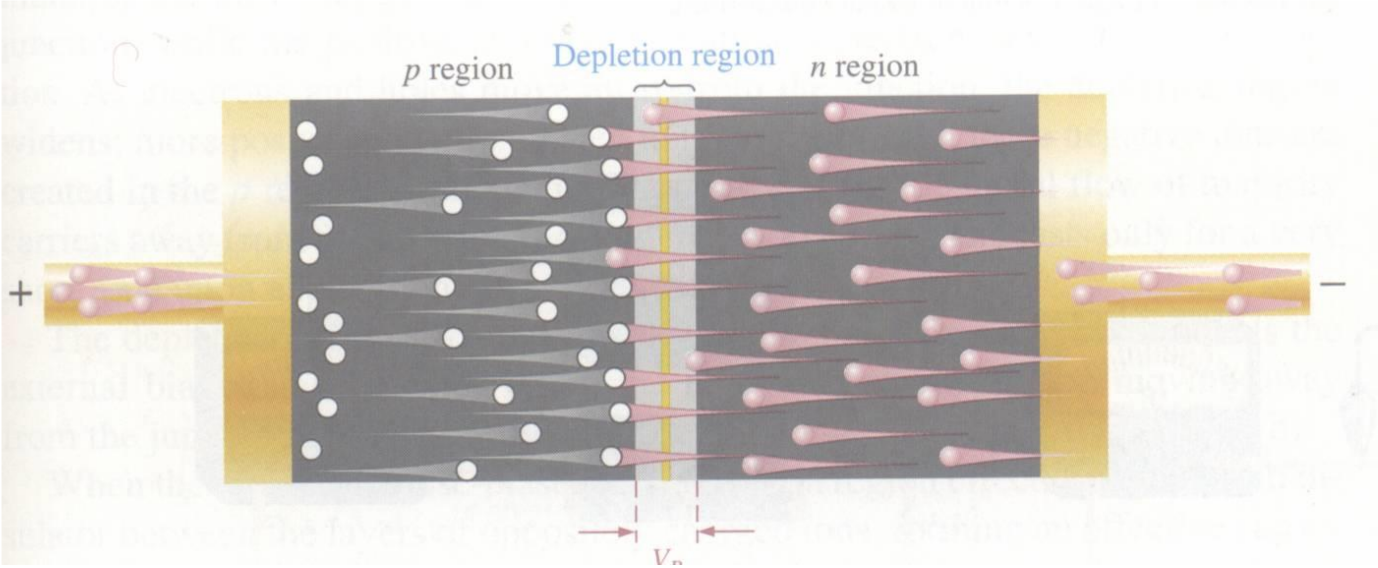
During the forward bias the following process occurs. The positive of the battery pumps more holes into the P-region of the diode. The negative terminal pumps electrons into the N-region.

The excess of charge in P and N region will apply pressure on the depletion region and will make it shrink. As the voltage increases the depletion layer will become thinner and thinner and hence diode will offer lesser and lesser resistance. Since the resistance decreases the current will increase (though not proportional to the voltage).

At one particular voltage level (Vf called as threshold / cut-off voltage) the depletion layer disappears and from this point on the diode starts to conduct very easily. From this point on the diode, current increases exponentially to the voltage applied.

Forward Bias

Positive terminal of DC voltage is connected to the p region and negative terminal is connected to the n region. It is the condition that **permits current** through the pn-junction of a diode.

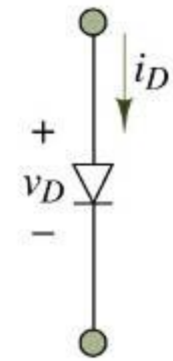


Biasing the PN-Junction

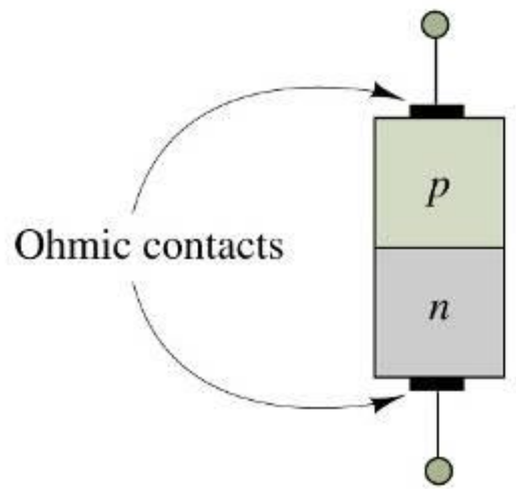
There is no movement of charge through a pn-junction at equilibrium.

The pn-junction form a *diode* which allows current in only one direction and prevent the current in the other direction.

The arrow in the circuit symbol for the diode indicates the direction of current flow when the diode is forward-biased.



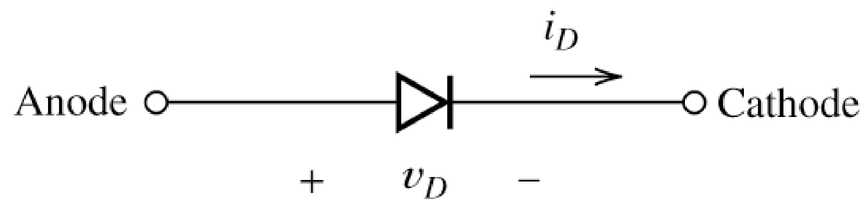
Circuit symbol

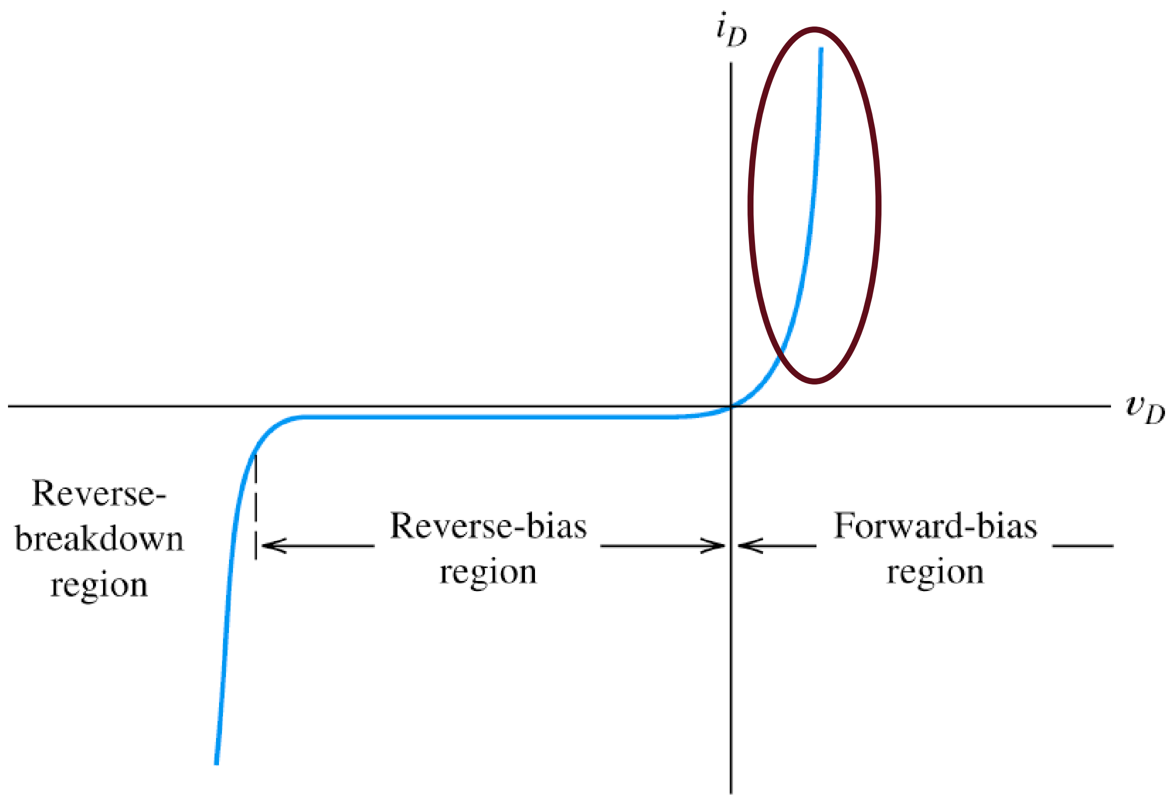


pn junction

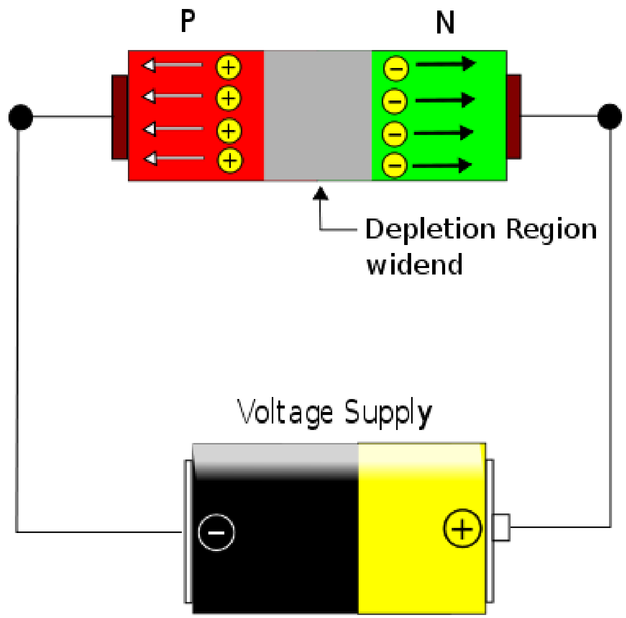
Biasing the PN-Junction

Forward Bias:





Reverse Bias

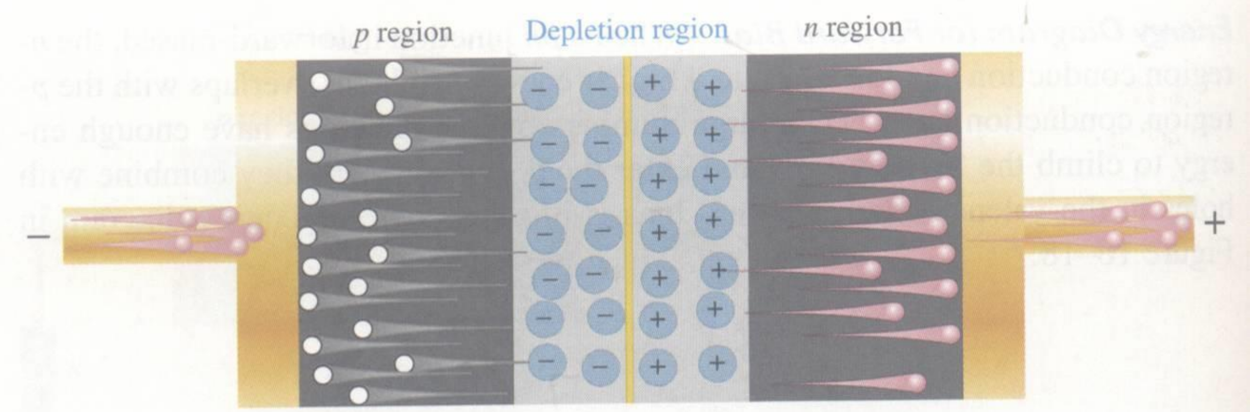


In reverse bias the P-type region is connected to negative voltage and N-type is connected to positive terminal as shown above. In this condition the holes in P-type gets filled by electrons from the battery / cell (in other words the holes get sucked out of the diode).

The electrons in N-type material is sucked out of the diode by the positive terminal of the battery. So the diode gets depleted of charge. So initially the depletion layer widens (see image above) and it occupies the entire diode. The resistance offered by the diode is very huge. The current that flows in reverse bias is only due to minority charge which is in nano amperes in silicon and micro amperes in high power silicon and germanium diodes.

Reverse Bias

DC voltage negative terminal connected to the p region and positive to the n region. Depletion region widens until its potential difference equals the bias voltage, majority-carrier current ceases.

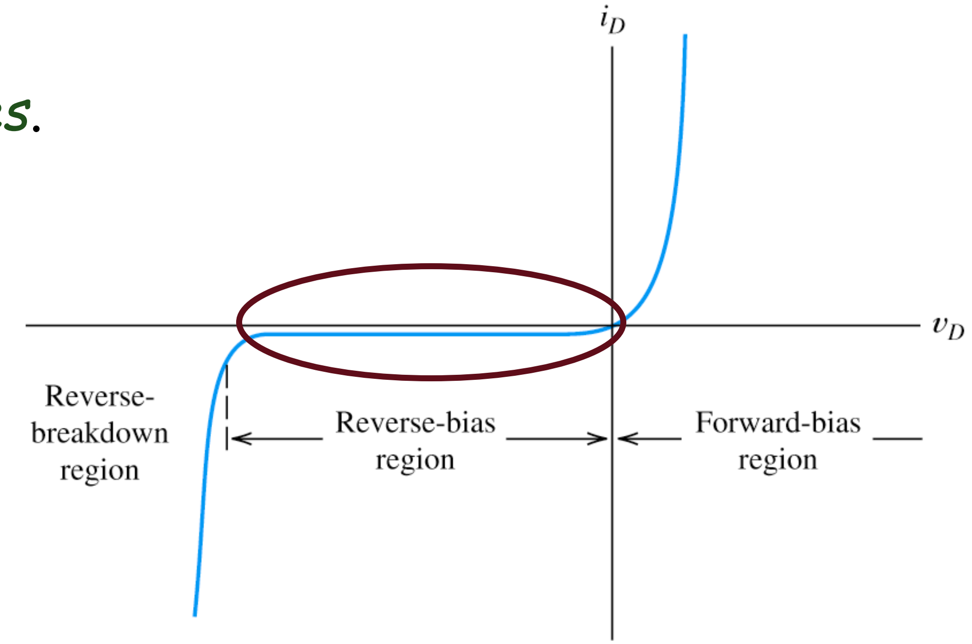


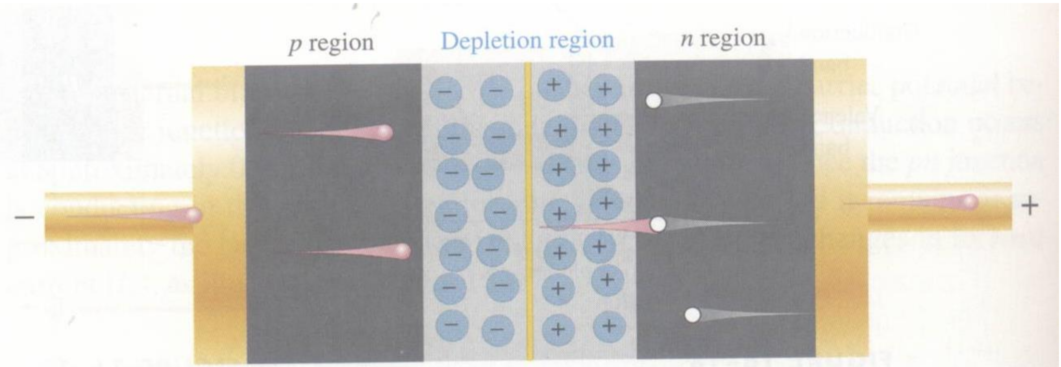
(a) There is transient current as depletion region widens.

Reverse Bias

Majority-carrier current ceases.

However, there is still a very small current produced by minority carriers.

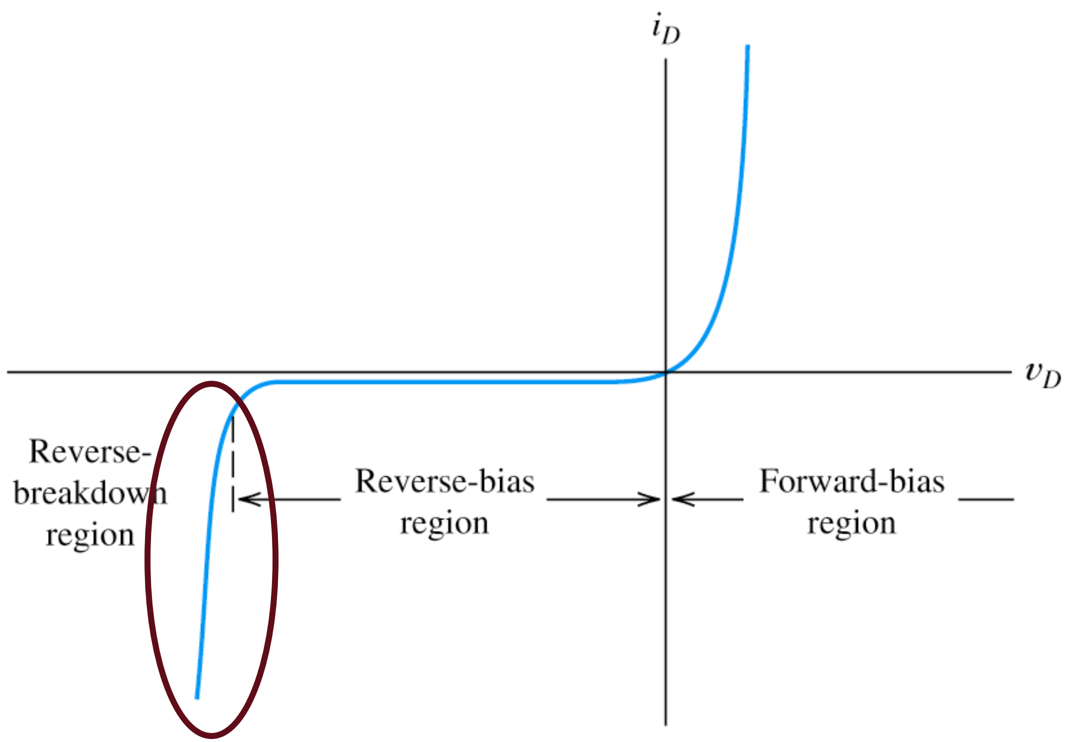




(b) Majority current ceases when barrier potential equals bias voltage. There is an extremely small reverse current due to minority carriers.

Biasing the PN-Junction

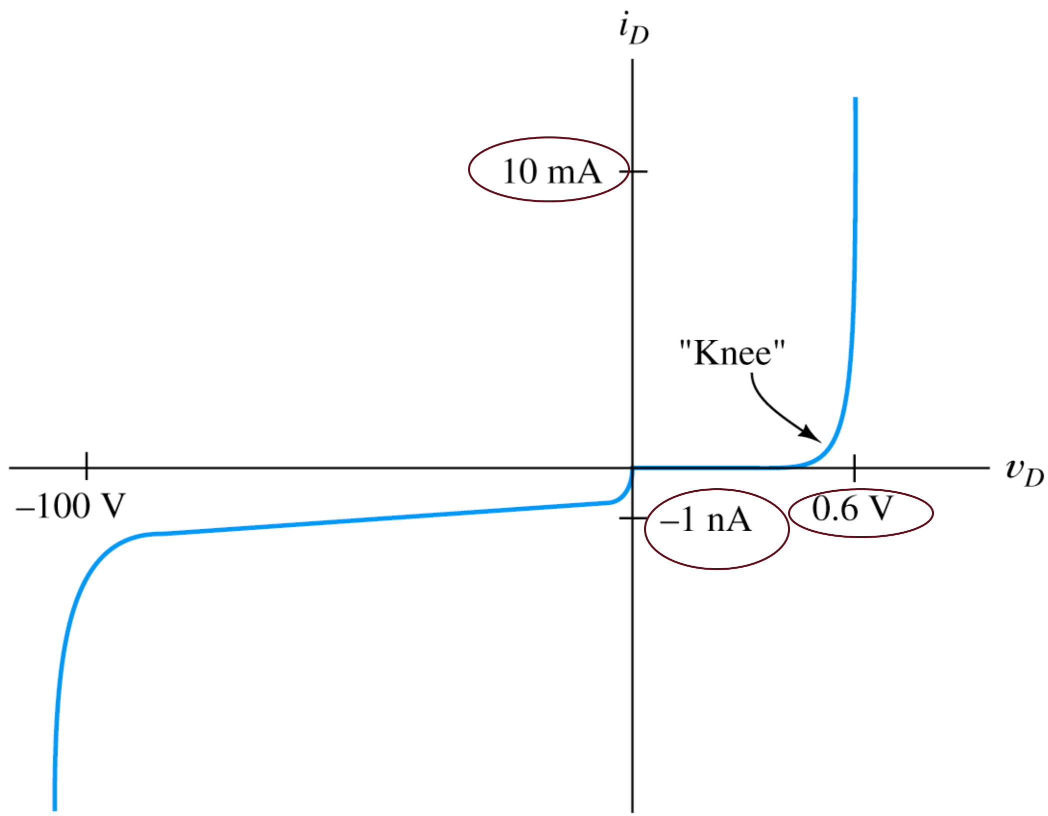
Reverse Breakdown: As reverse voltage reach certain value, avalanche occurs and generates large current.



(b) Volt–ampere characteristic

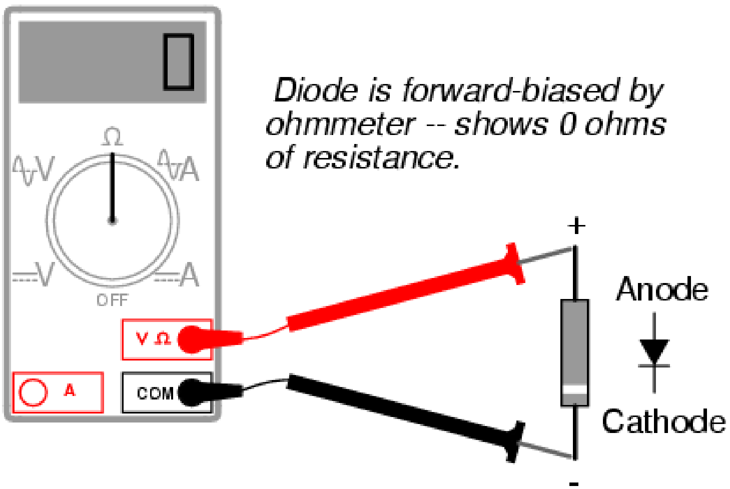
If the reverse voltage is made high enough, then the junction will break down and electrons will flow from anode to cathode (under normal conditions, electrons flow from cathode to anode, when forward biased).

The Diode Characteristic I-V Curve

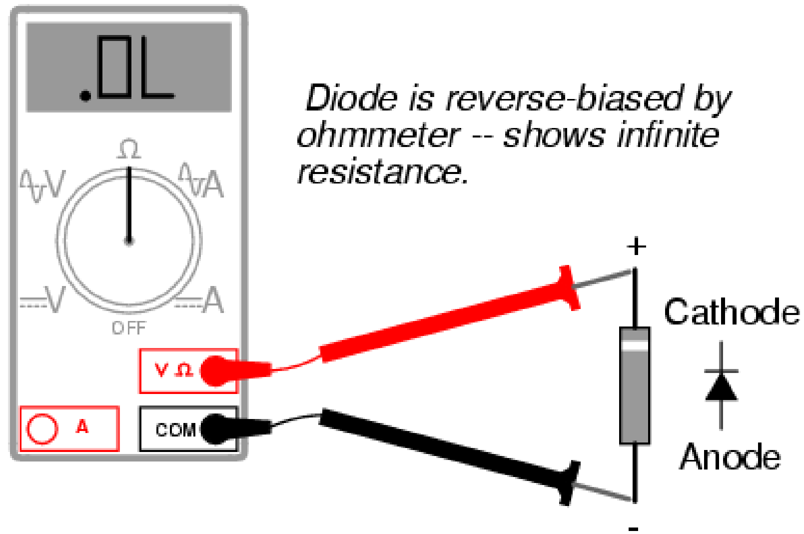


Volt–ampere characteristic for a typical small-signal silicon diode at a temperature of 300 K. Notice the change of scale for negative current and voltage.

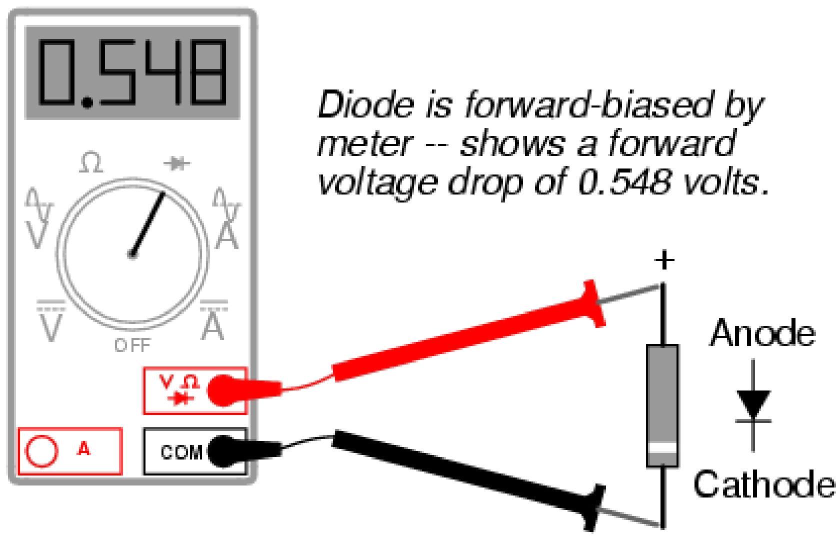
Diode – Characteristic



Diode is forward-biased by ohmmeter -- shows 0 ohms of resistance.

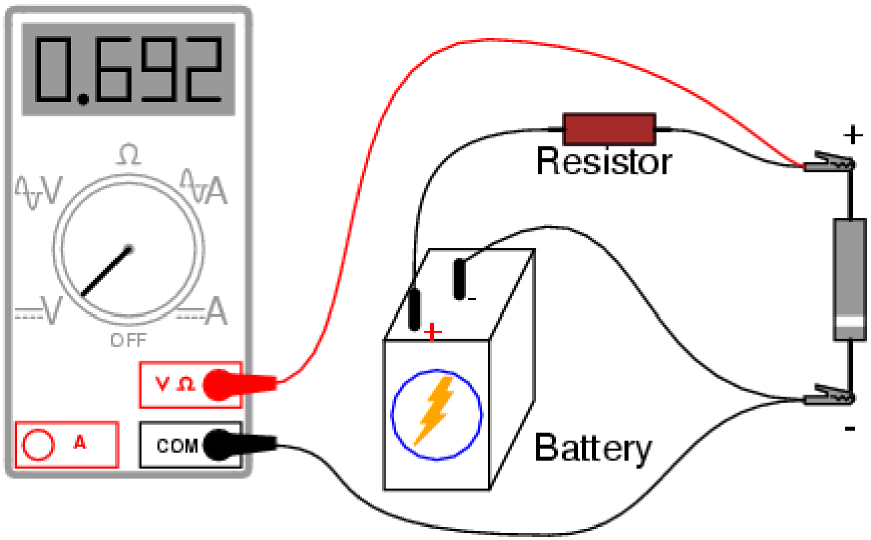


Diode is reverse-biased by ohmmeter -- shows infinite resistance.

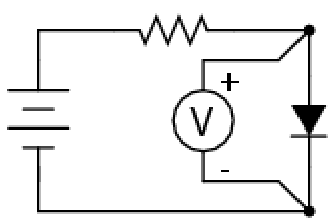


Diode is forward-biased by meter -- shows a forward voltage drop of 0.548 volts.

Diode – Characteristic

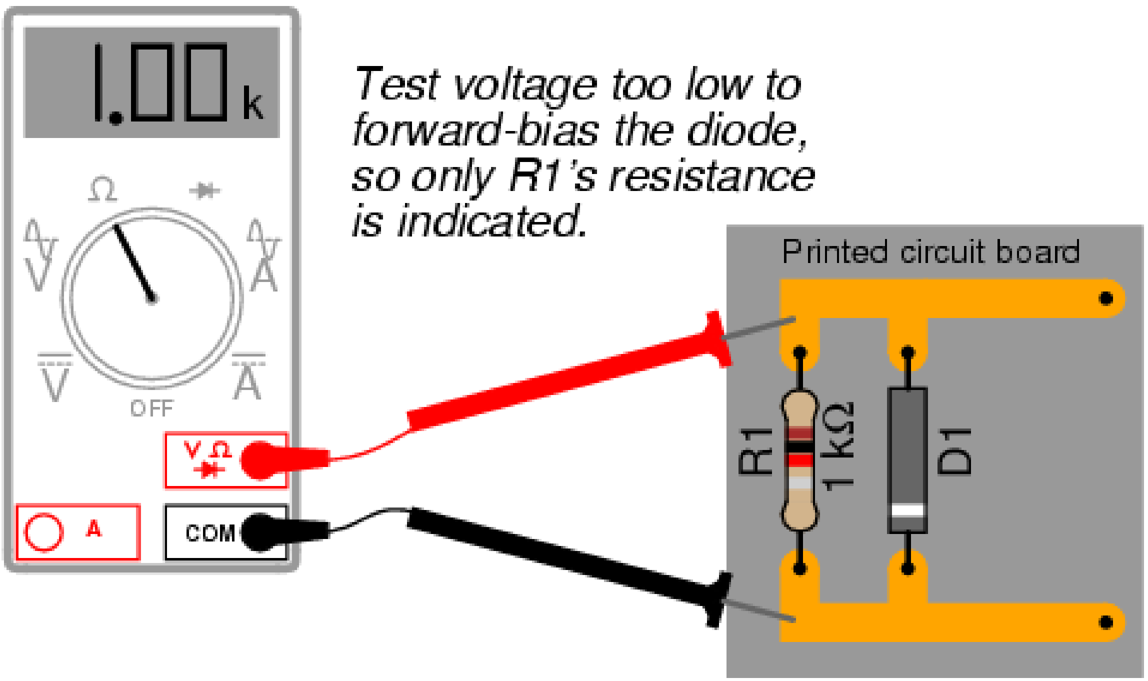


Schematic diagram

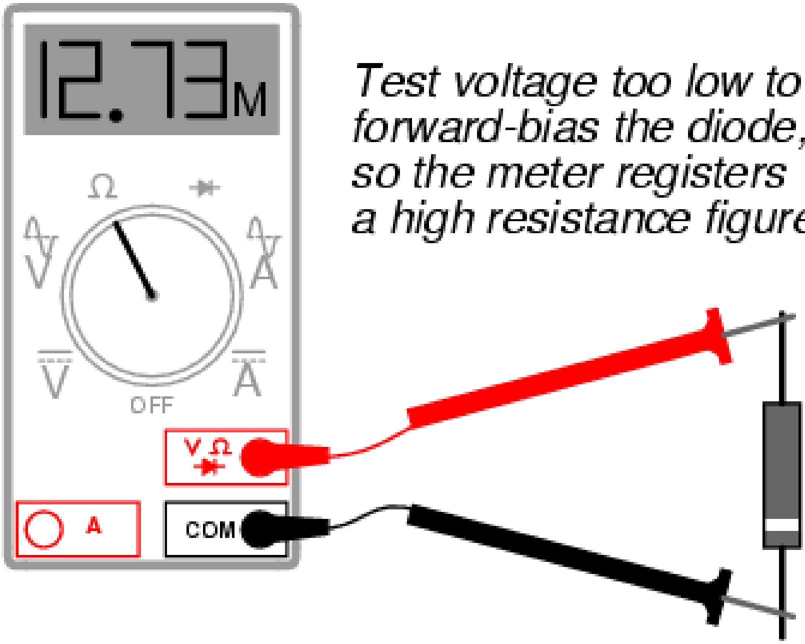


Resistor sized to obtain diode current of desired magnitude.

Diode – Characteristic



Diode – Characteristic



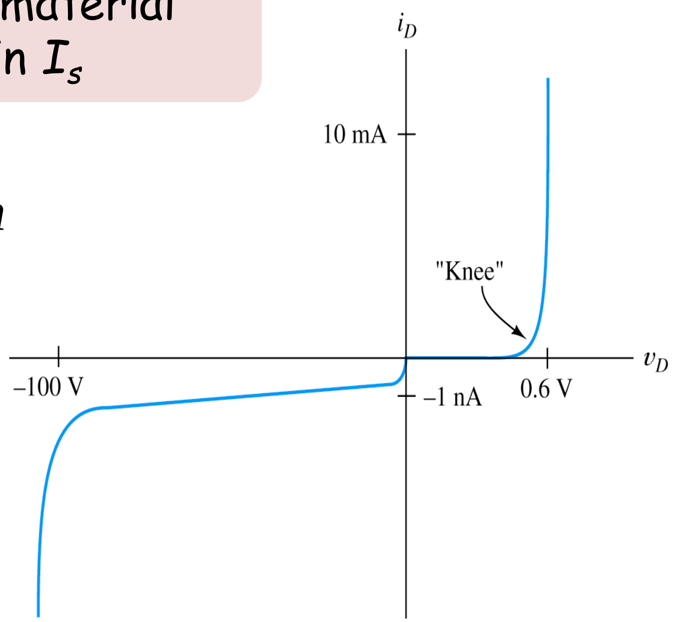
Test voltage too low to forward-bias the diode, so the meter registers a high resistance figure.

Shockley Equation

* The Shockley equation is a theoretical result under certain simplification:

$$\boxed{i_D = I_s\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right]}$$

Geometry, doping and material constants are lumped in I_s



$$where\ I_s \cong 10^{-14}\ A\ at\ 300K\ is\ the\ (reverse)\ saturation$$

$$current,\ n \cong 1\ to\ 2\ is\ the\ emission\ coefficient,$$

$$V_T = \frac{kT}{q} \cong 0.026V\ at\ 300K\ is\ the\ thermal\ voltage$$

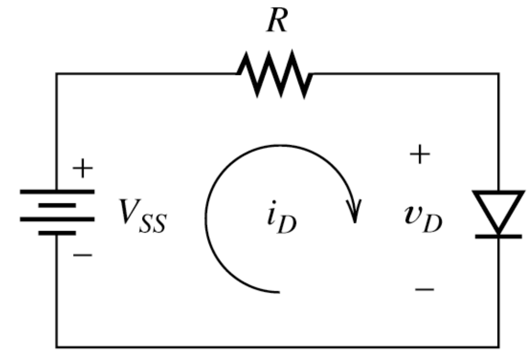
$$k\ is\ the\ Boltzman's\ constant,\ q = 1.60 \times 10^{-19}\ C$$

$$when\ \boxed{v_D \geq\approx 0.1V,\ i_D \cong I_s \exp\left(\frac{v_D}{nV_T}\right)}$$

$$This\ equation\ is\ not\ applicable\ when\ v_D < 0$$

Load-Line Analysis of Diode Circuit

We can use $v = iR,\ i = C\dfrac{dv}{dt},\ v = L\dfrac{di}{dt}, \ldots$



but when there is a diode: $i_D = I_s\left[\exp\left(\dfrac{v_D}{nV_T}\right) - 1\right]$

It is difficult to write KCL or KVL equations.

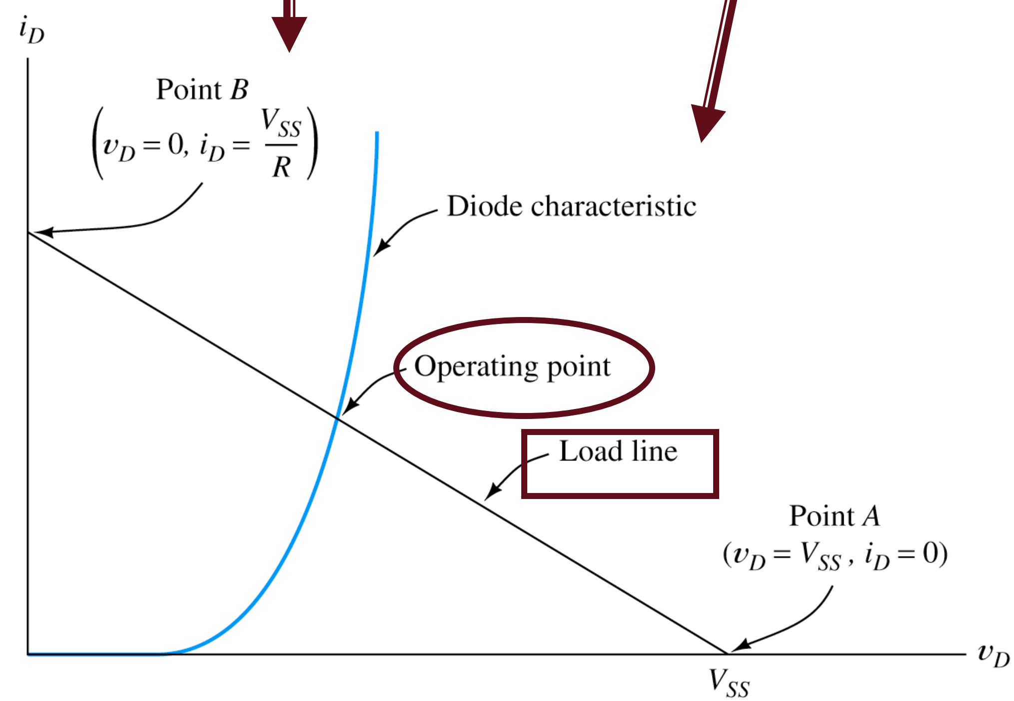
For the circuit shown,

KVL gives:

$$\boxed{V_{SS} = Ri_D + v_D}$$

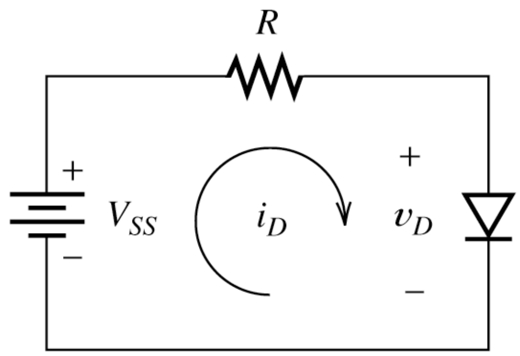
If the I-V curve of the diode is given, we can perform the

"Load-Line Analysis"



Example Load-Line Analysis

$$
\begin{aligned}
&\text{For the circuit shown,}\\
&\text{Given}: V_{SS} = 2V, R = 1k\Omega,\\
&\qquad \text{the } I\text{-}V \text{ curve of the diode}\\
&\text{Find}: \text{the diode current and voltage}\\
&\qquad \text{at the operating point (Q - point)}
\end{aligned}
$$



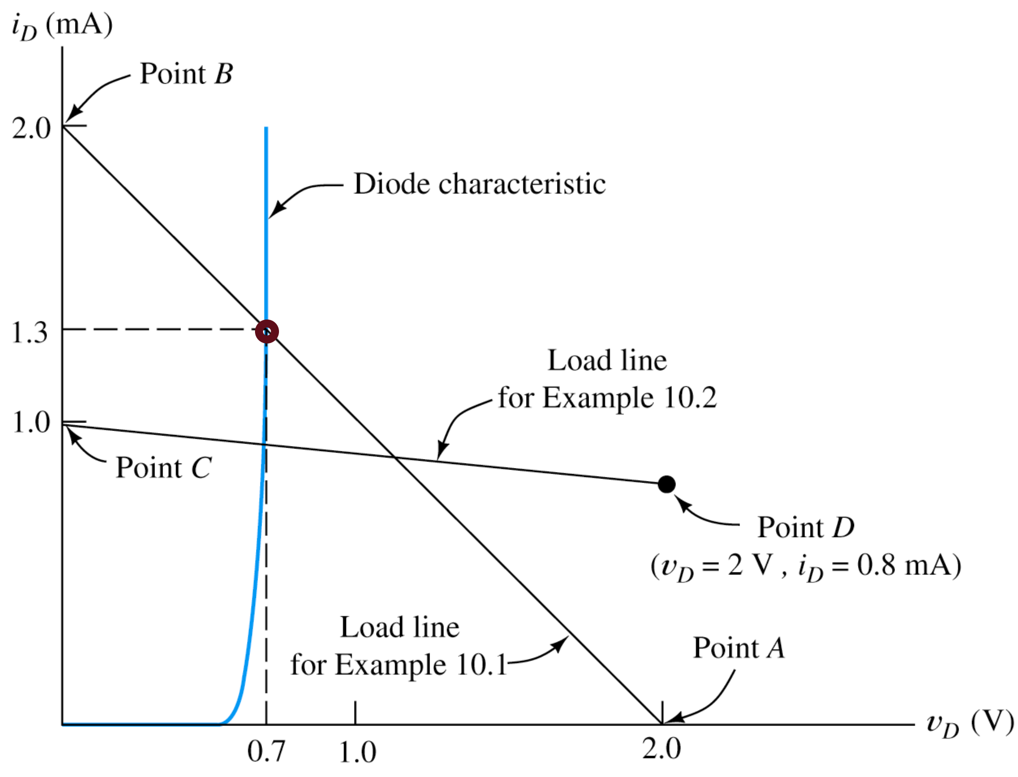
$$V_{SS} = R\,i_D + v_D, \text{ i.e.,}$$

$$2 = 1000\,i_D + v_D$$

$$\Rightarrow \text{perform load - line analysis}$$

$$\Rightarrow \text{at the operating point}$$

$$\boxed{V_{DQ} \cong 0.70\,V,\ i_{DQ} \cong 1.3\,mA}$$



Example Load-Line Analysis

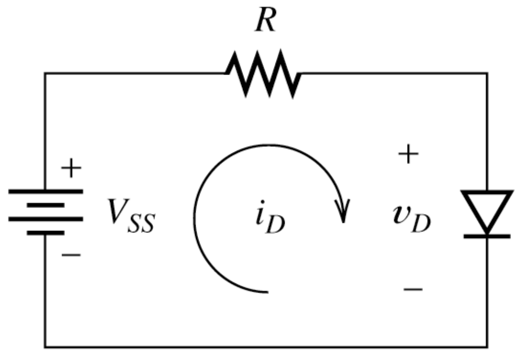
For the circuit shown,

Given : $Vss = 10\,V, R = 10\,k\Omega,$

the I - V curve of the diode

Find : the diode current and voltage

at the operating point



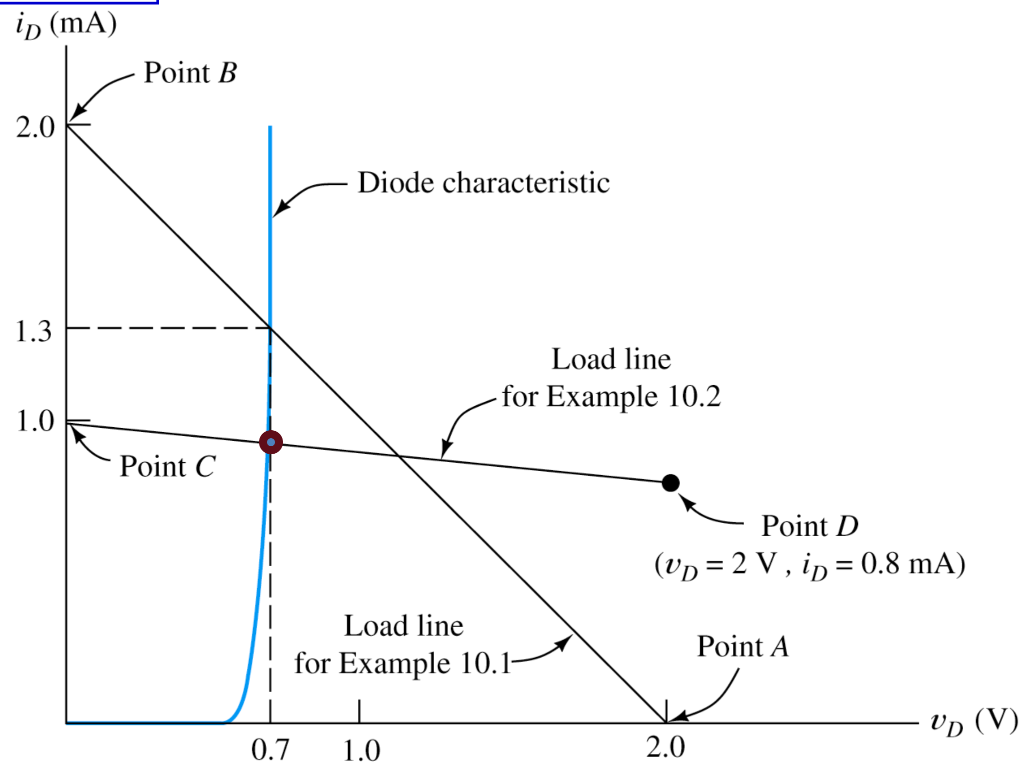
$$V_{SS} = R\,i_D + v_D,\ i.e.,$$

$$10 = 10k\,i_D + v_D$$

$\Rightarrow$ *perform load - line analysis*

$\Rightarrow$ *at the operating point*

$$\boxed{V_{DQ} \cong 0.68\,V,\ i_{DQ} \cong 0.93\,mA}$$

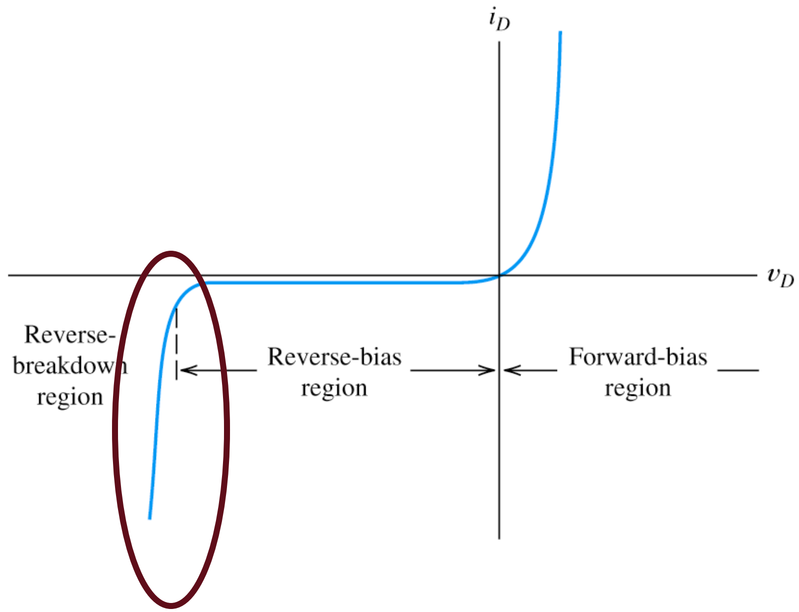


The Zener Diode

* *Zener diode* is designed for operation in the reverse-breakdown region.

* The *breakdown voltage* is controlled by the doping level *(-1.8 V to -200 V)*.

* The major application of Zener diode is to provide an output reference that is stable despite changes in input voltage – power supplies, voltmeter,…



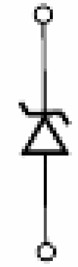


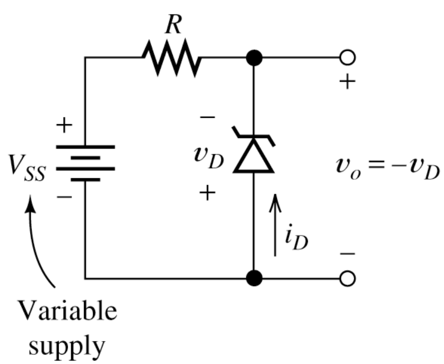
Figure 7.3 Zener diode symbol.

Zener-Diode Voltage-Regulator Circuits

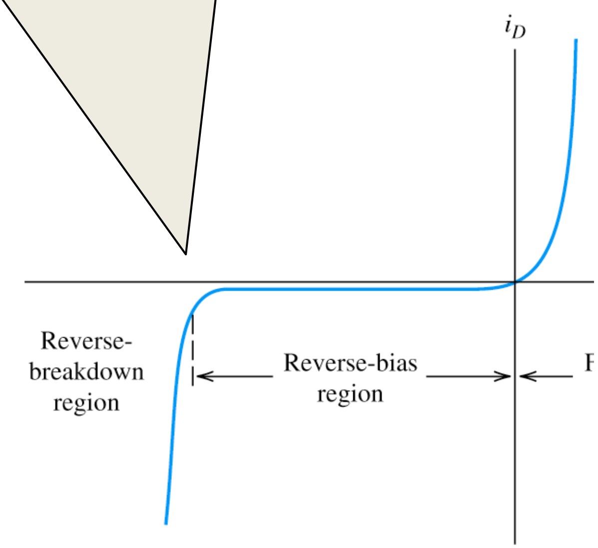
Sometimes, a circuit that produces constant output voltage while operating from a variable supply voltage is needed. Such circuits are called *voltage regulator*.

The resistor limits the diode current to a safe value so that Zener diode does not overheat.

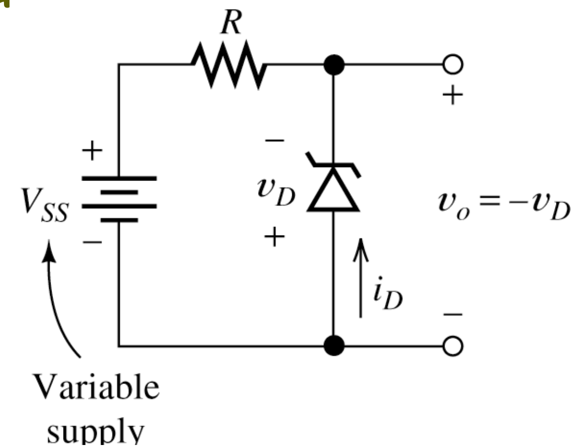
The Zener diode has a breakdown voltage equal to the desired output voltage.



A simple regulator circuit that provides a nearly constant output voltage v_o from a variable supply voltage.



Example – Zener-Diode Voltage-Regulator Cir



Given : the Zener diode I-V curve, $R = 1k\Omega$

Find : the output voltage for $V_{SS} = 15\,V$ and

$V_{SS} = 20\,V$

KVL gives the load line :

$$V_{SS} + R\,i_D + v_D = 0$$

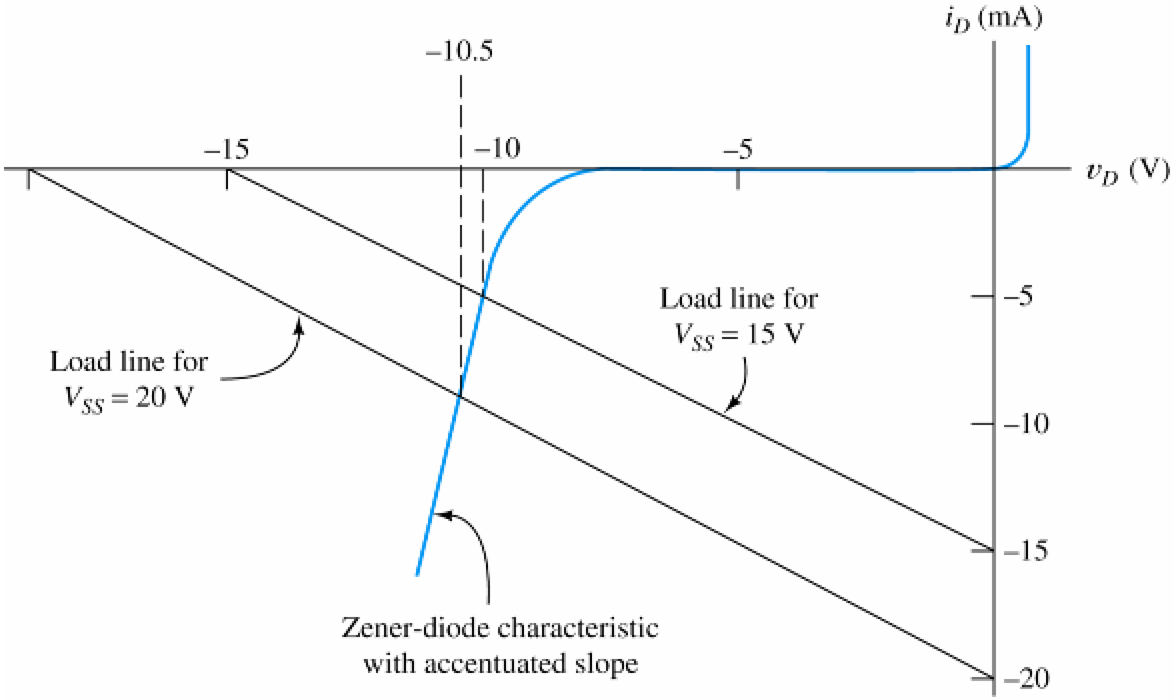
From the Q - point we have :

$$v_o = 10.0\,V \ \text{ for } V_{SS} = 15\,V$$

$$v_o = 10.5\,V \ \text{ for } V_{SS} = 20\,V$$

5V change in input

$\Rightarrow 0.5V$ change in v_o



Actual Zener diode performs much better!

Ideal-Diode Model

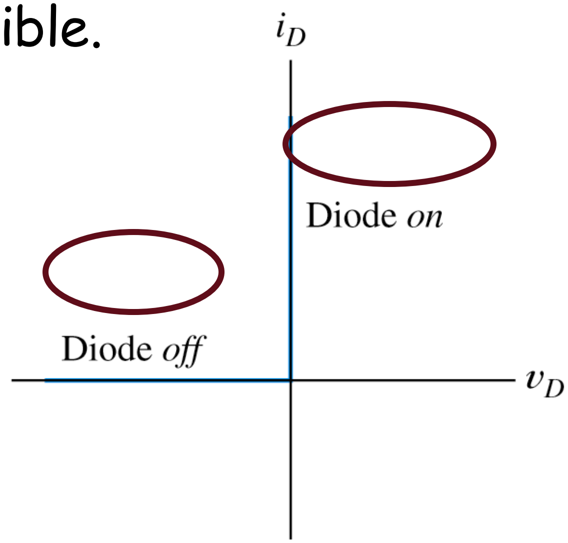
* Graphical load-line analysis is too cumbersome for complex circuits,

•We may apply "*Ideal-Diode Model*" to simplify the analysis:

(1) in forward direction: *short-circuit assumption*, zero voltage drop;

(2) in reverse direction: *open-circuit assumption*.

* The ideal-diode model can be used when the forward voltage drop and reverse currents are negligible.



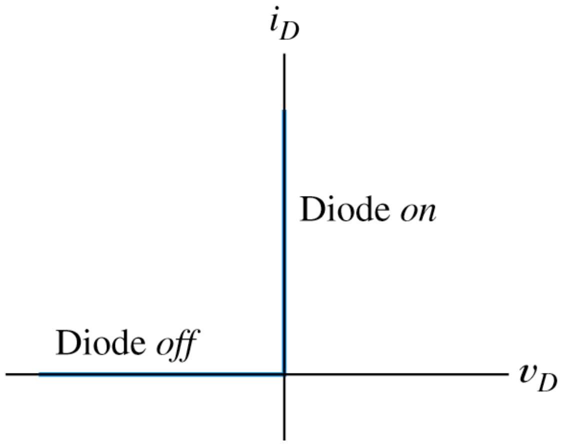
Ideal-diode volt–ampere characteristic.

Ideal-Diode Model

* In analysis of a circuit containing diodes, we may not know in advance *which diodes are on and which are off*.

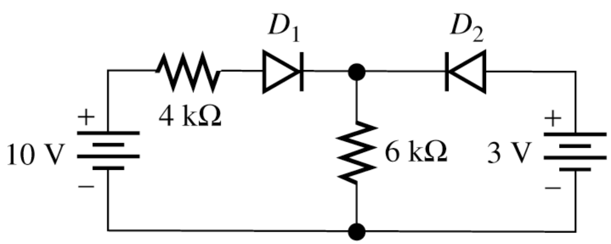
* What we do is first to make a guess on the state of the diodes in the circuit:

$$
\boxed{\begin{array}{l}
(1)\ For\ \text{"}assumed\ on\ diodes\text{"}:\ check\ if\ i_D\ is\ positive; \\
(2)\ For\ \text{"}assumed\ off\ diodes\text{"}:\ check\ if\ v_D\ is\ negative \\
\Rightarrow ALL\ YES \Rightarrow BINGO! \\
\Rightarrow not\ ALL\ YES \Rightarrow make\ another\ guess.... \\
\qquad\qquad\qquad iterates\ until\ \text{"}ALL\ YES\text{"}
\end{array}}
$$



Example – Analysis by Assumed Diode States

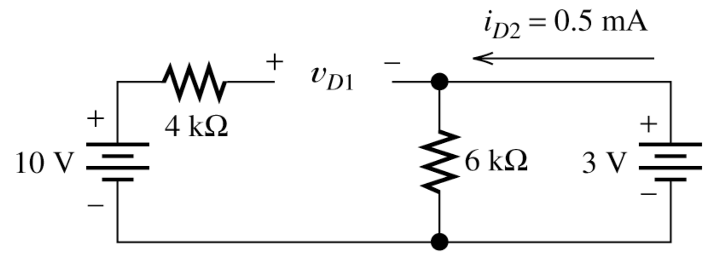
Analysis the circuit by assuming D_1 is off and D_2 on



(a) Circuit diagram

(1) assume

$D_1 off,\ D_2\ on \Rightarrow$



(b) Equivalent circuit assuming D_1 off and D_2 on (since $v_{D1} = +7$ V, this assumption is not correct)

$\Downarrow$

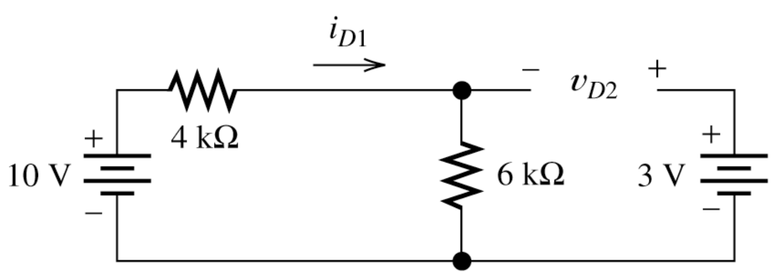
$$i_{D2} = 0.5mA \quad OK!$$

$$v_{D1} = 7V \quad not\ OK!$$

$\Downarrow$

(2) assume

$D_1\ on,\ D_2\ off$



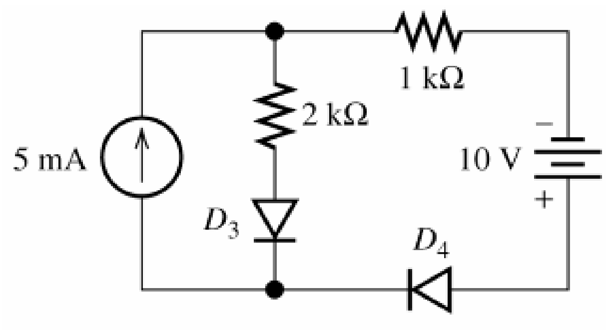
(c) Equivalent circuit assuming D_1 on and D_2 off (this is the correct assumption since i_{D1} turns out to be a positive value and v_{D2} turns out negative)

$$\Rightarrow\ i_{D1} = 1\,mA \quad OK!$$

$$v_{D2} = -3\,V \quad OK!$$

Quiz – Exercise

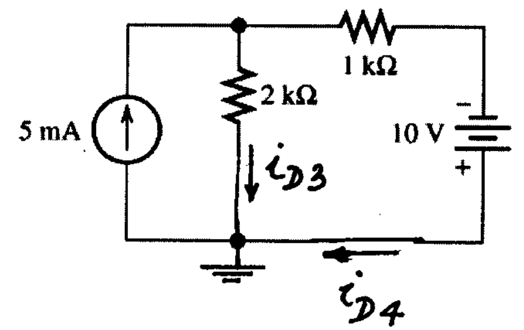
* Find the diode states by using ideal-diode model. Starting by assuming both diodes are on.



(1) *assume*

D_3 *on* $\Rightarrow$

D_4 *on*



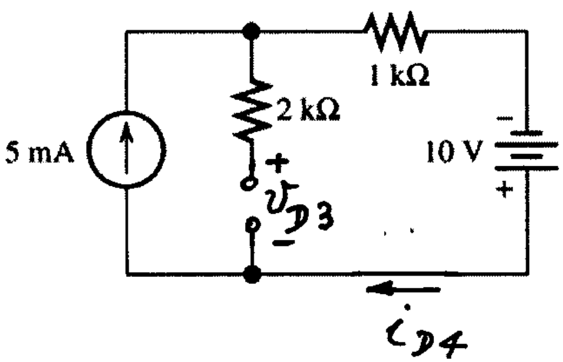
$\Downarrow$

$i_{D3} = \text{-}1.7\ mA$, *not OK*

$i_{D4} = 6.7\ mA$, *OK*

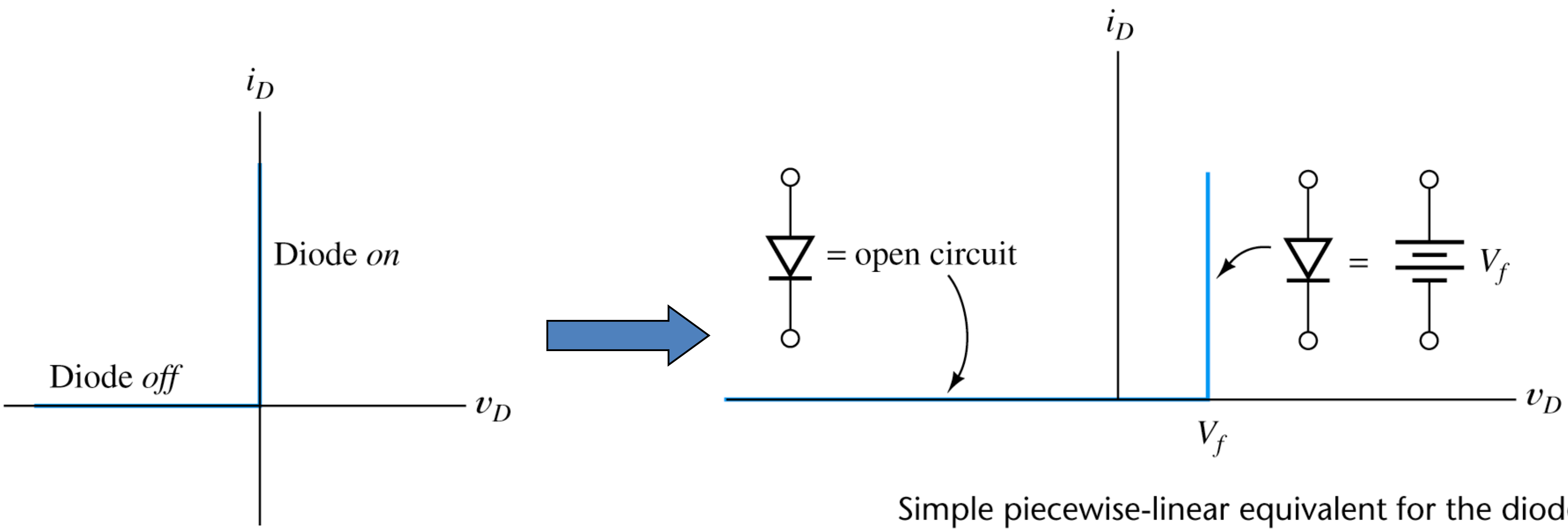
(2) *assume* D_3 *off* *and* D_4 *on*

$\Downarrow$



$$\boxed{\begin{aligned} \Rightarrow\ i_{D4} &= 5\ mA, \quad OK \\ v_{D3} &= \text{-}5\,V, \quad OK \end{aligned}}$$

Modified Ideal-Diode Model



Simple piecewise-linear equivalent for the diode.

Modified ideal-diode model is usually accurate enough in most of the circuit analysis.

Piecewise Linear Diode Models

More accurate that the ideal diode model and do not relies on nonlinear equation or graphical techniques.

(1) Diode V-I ch-tic approximated by straight line segments

(2) We model each section of the diode I-V ch-tic with R in series with a fixed voltage source

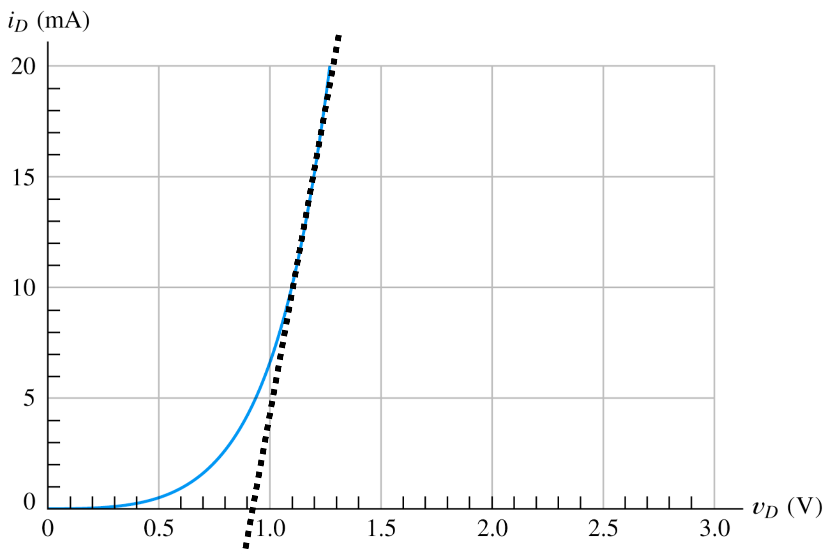


Figure 10.8 Diode characteristic for Exercise 10.3.

$$v = R_a i + V_a$$

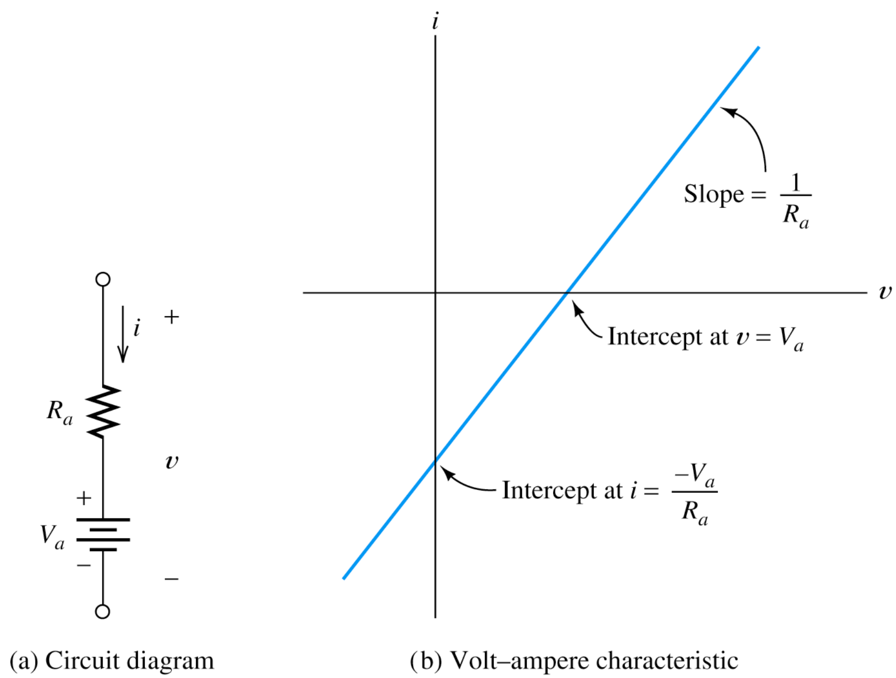


Figure 10.18 Circuit and volt–ampere characteristic for piecewise-linear models.

Problem

Find circuit models for the Zener-diode volt-ampere ch-tic shown in figure below using the piecewise-linear diode model.

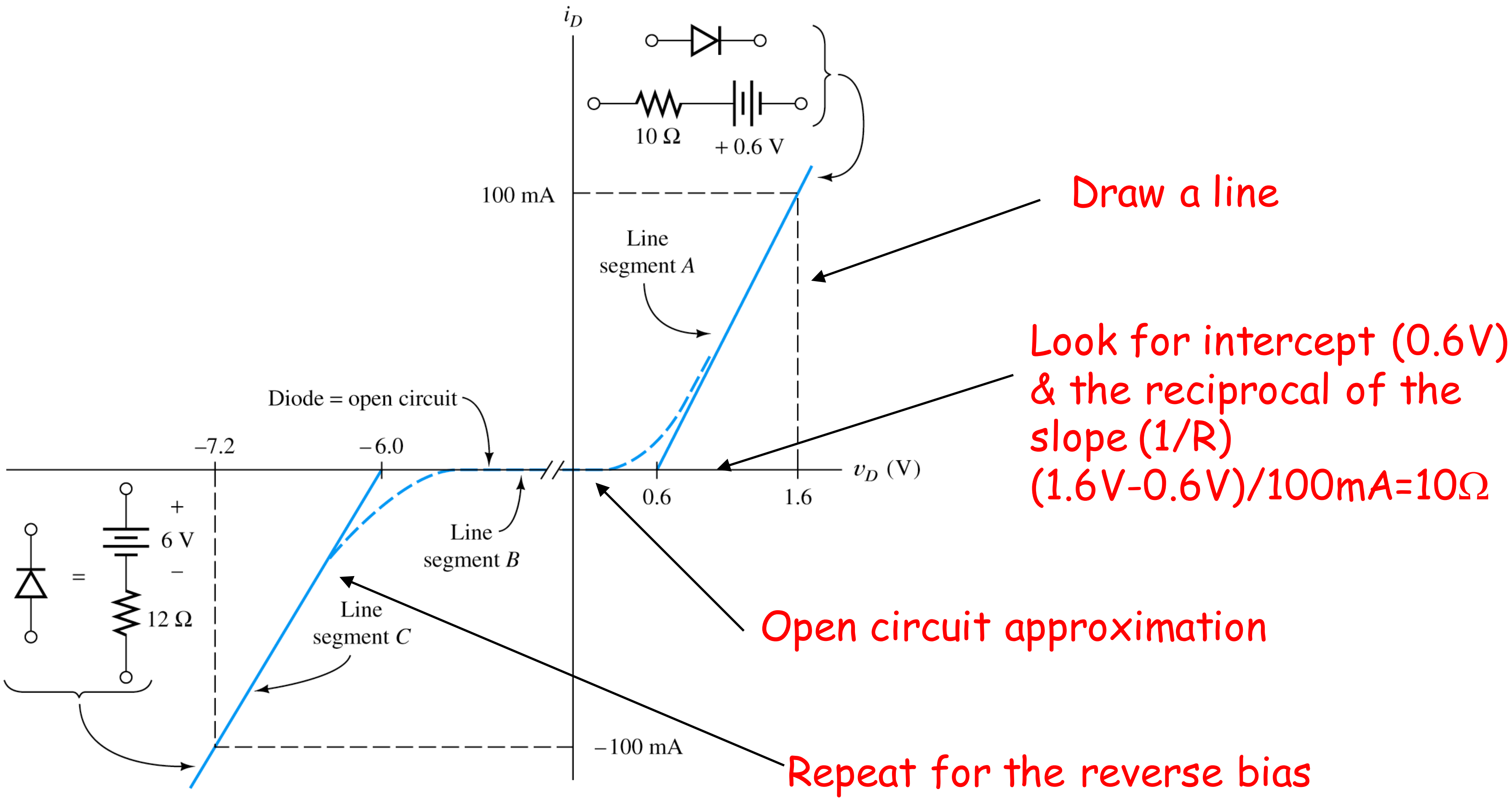


Figure 10.19 Piecewise-linear models for the diode of Example 10.6.

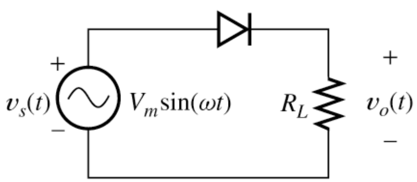
Exercise 10.7

Rectifier Circuits

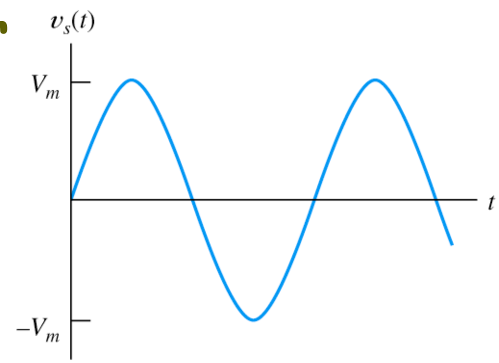
* *Rectifiers* convert ac power to dc power.

* Rectifiers form the basis for electronic power suppliers and battery charging circuits.

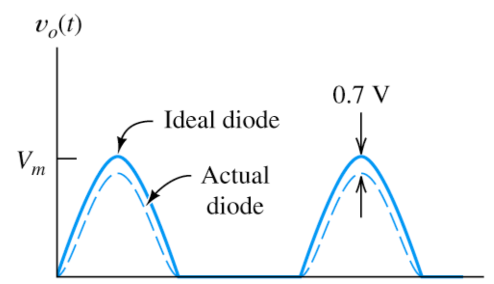
Half-Wave Rectifier



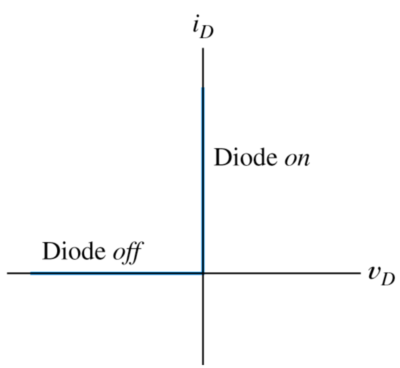
(a) Circuit diagram

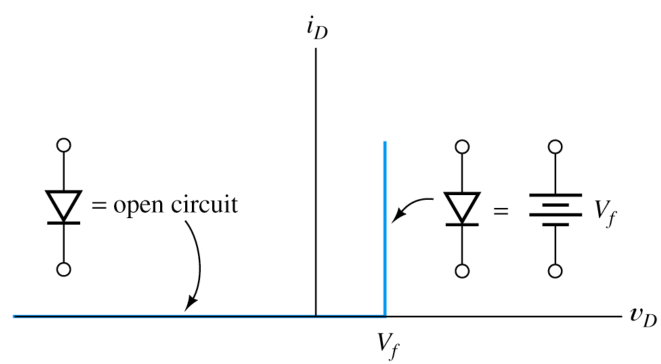


(b) Source voltage versus time

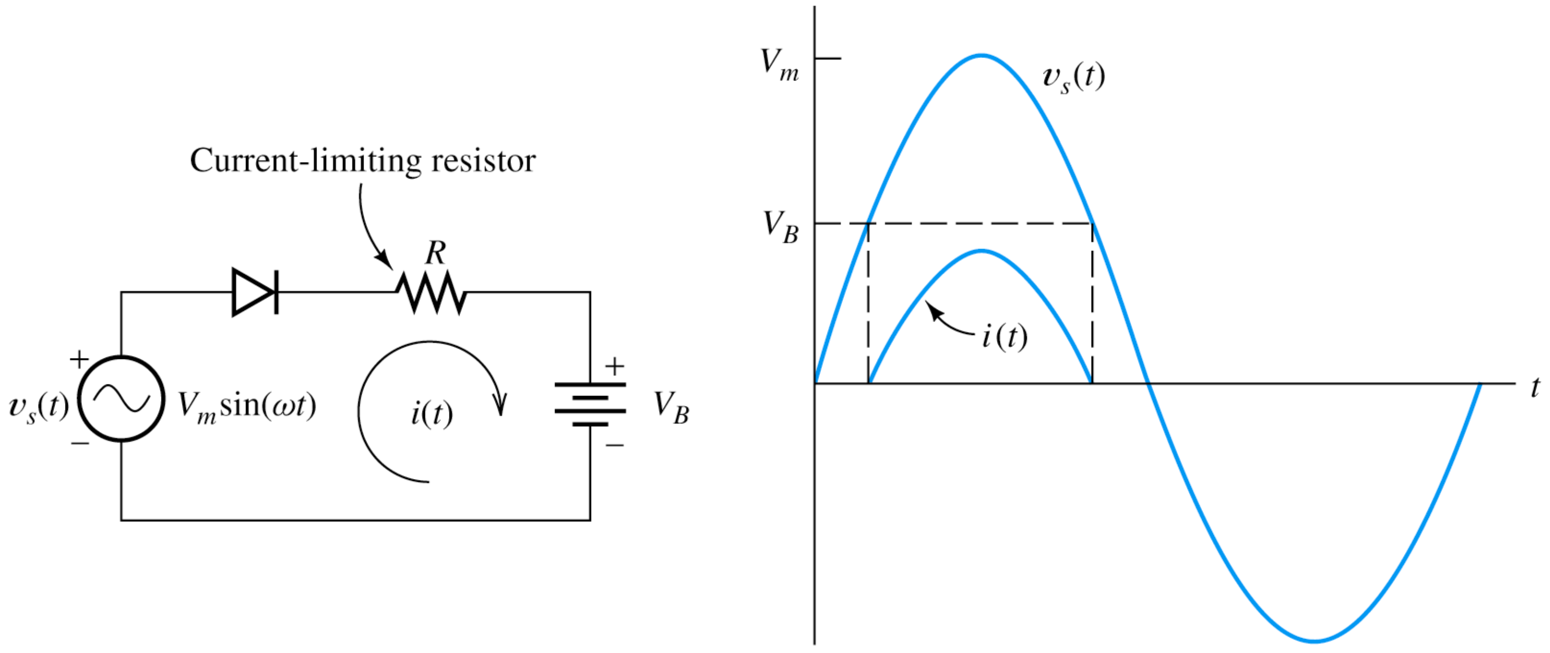


(c) Load voltage versus time





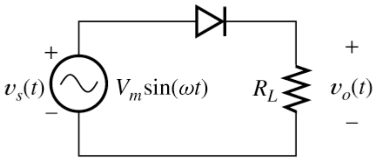
Basic Battery-Charging Circuit



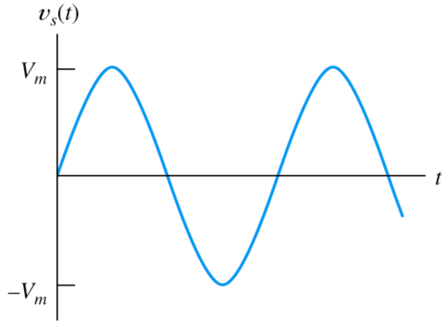
Half-wave rectifier used to charge a battery.

The current flows only in the direction that charges the battery.

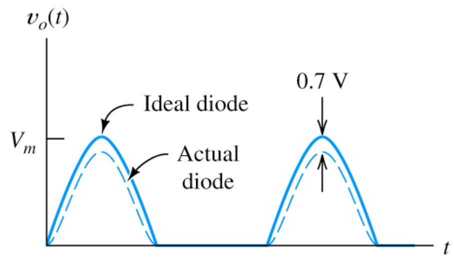
Half-Wave Rectifier with Smoothing Capacitor



(a) Circuit diagram

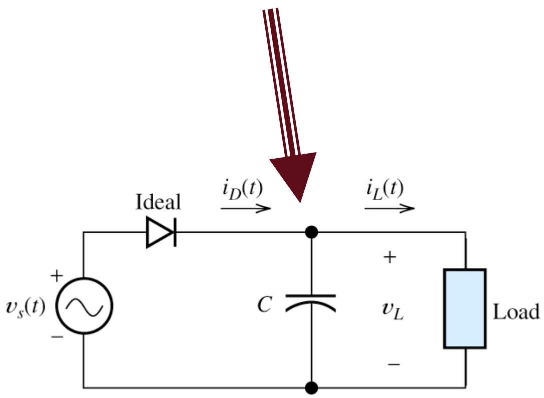


(b) Source voltage versus time

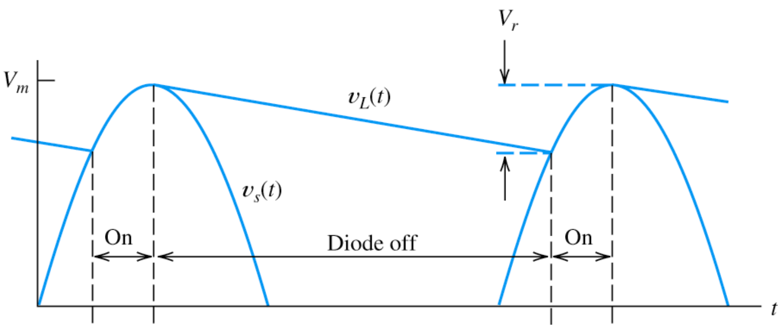


(c) Load voltage versus time

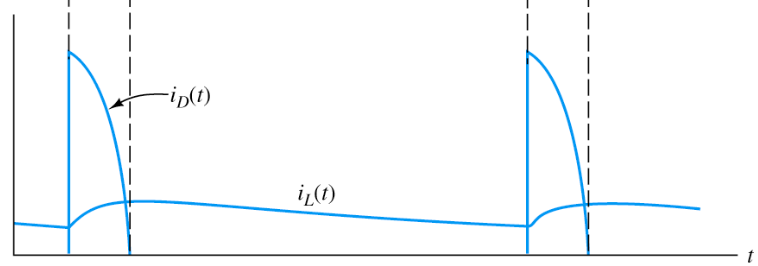
* To place a large capacitance across the output terminals:



(a) Circuit diagram



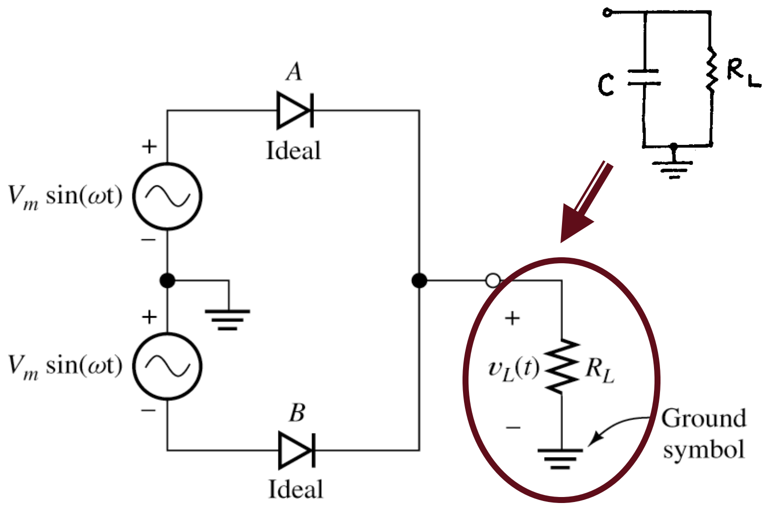
(b) Voltage waveforms



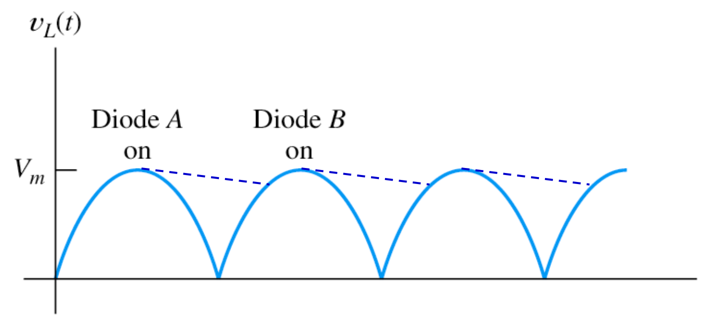
(c) Current waveforms

Full-Wave Rectifier Circuits

We can also smooth the output by using a large capacitance.



(a) Circuit diagram



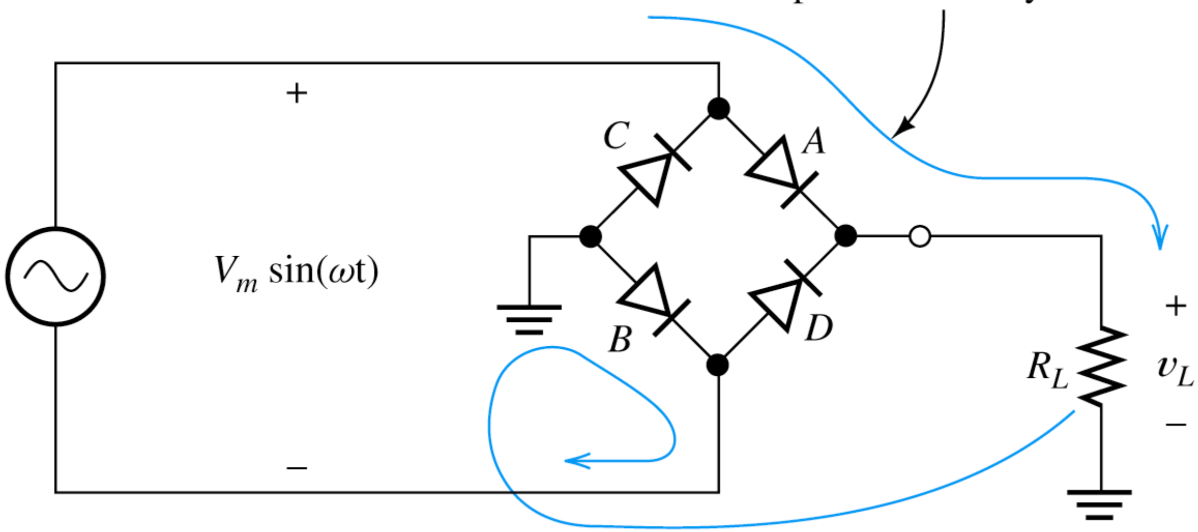
(b)

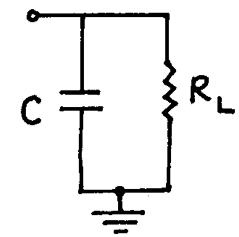
- *Center-Tapped Full-Wave Rectifier* – two half-wave rectifier with out-of-phase source voltages and a common ground.

* When upper source supplies "+" voltage to diode A, the lower source supplies "-" voltage to diode B; and vice versa.

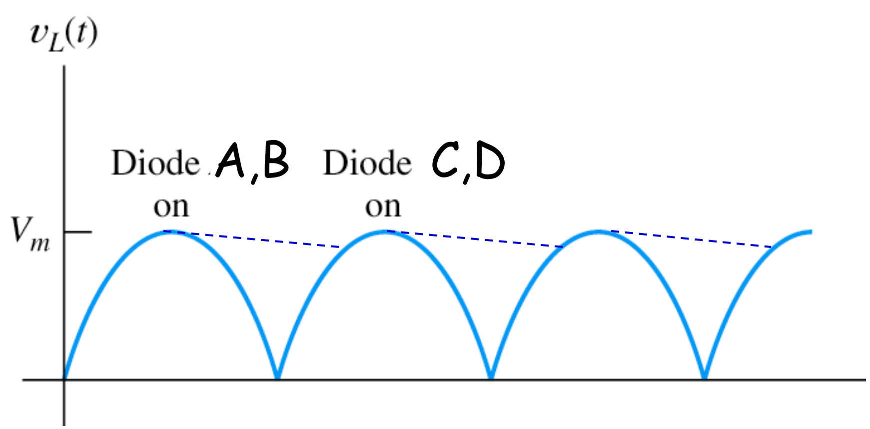
Full-Wave Rectifier Circuits

* The *Diode-Bridge Full-Wave Rectifier*:





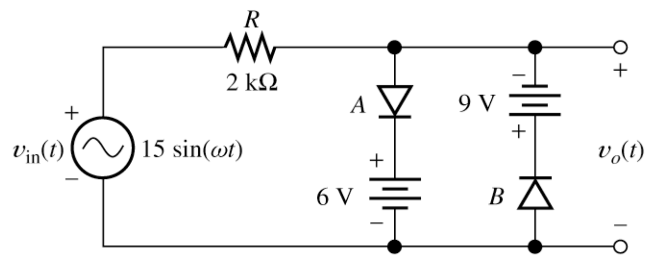
We can also smooth the output by using a large capacitance.



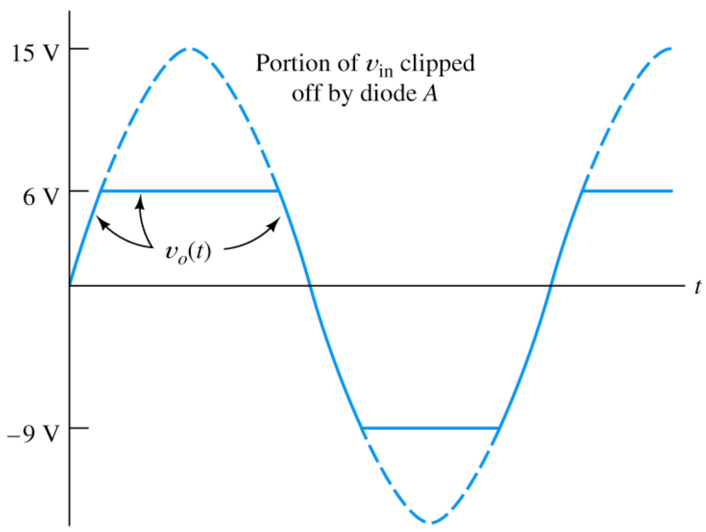
Wave-Shaping Circuits

Clipper Circuits

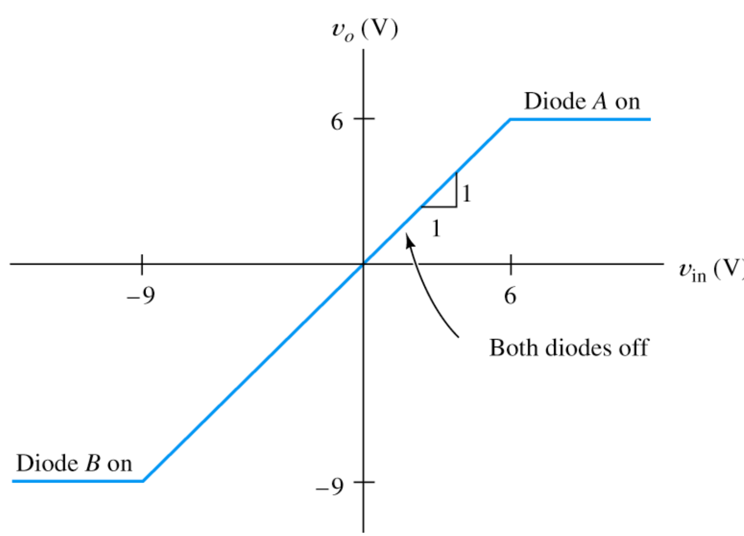
* A portion of an input signal waveform is "*clipped*" off.



(a) Circuit diagram



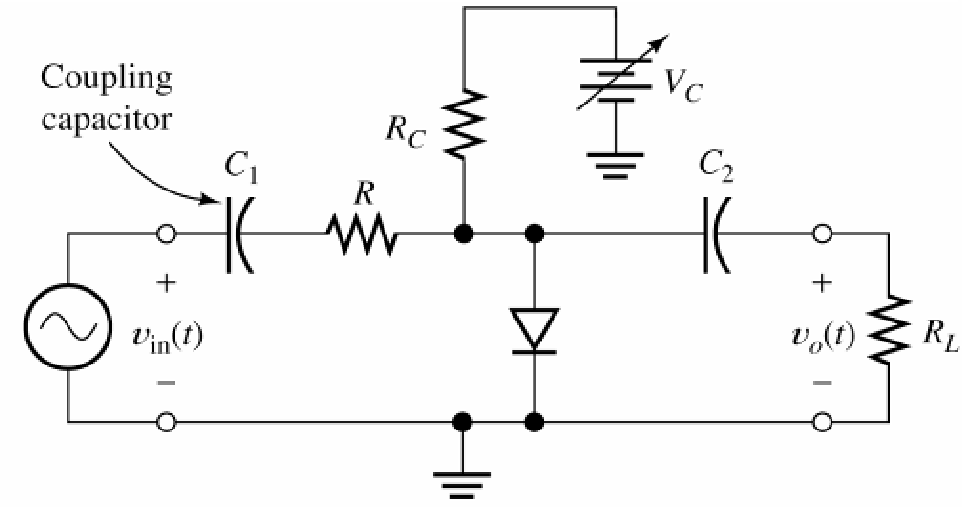
(b) Waveforms



(c) Transfer characteristic

Linear Small-Signal Equivalent Circuits

* In most of the electronic circuits, dc supply voltages are used to *bias* a nonlinear device at an *operating point* and a *small signal* is injected into the circuits.



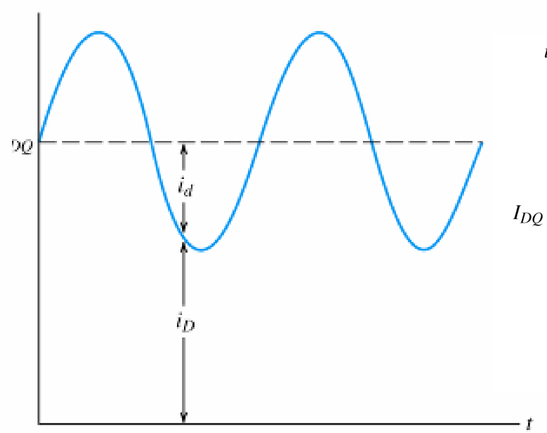
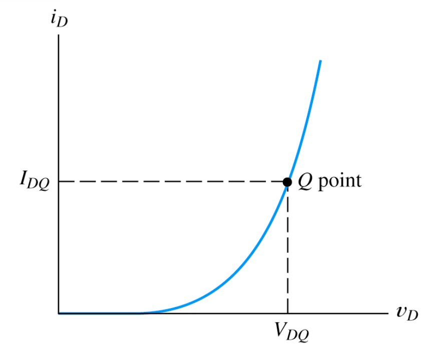


Figure 10.39 Illustration of diode currents.



* We often split the analysis of such circuit into two parts:
(1) Analyze the dc circuit to find operating point,
(2) Analyze the small signal (by using the "*linear small-signal equivalent circuit*".)

Linear Small Signal Equivalent Circuits

Since virtually any nonlinear curve is approximately linear (straight) if we consider a sufficiently small segment

THEN

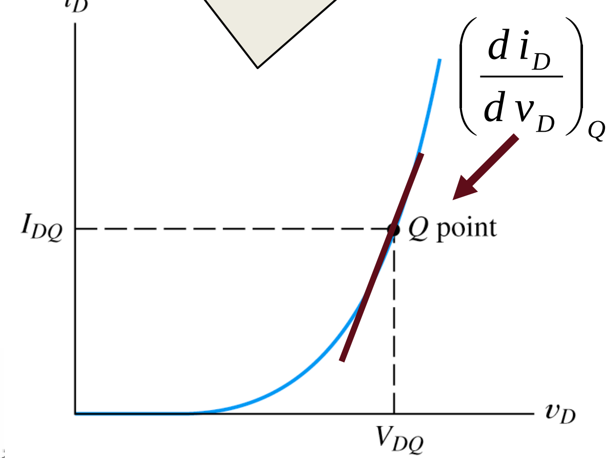
We can find a linear small-signal equivalent circuit for the nonlinear device to use in the ac analysis

The small signal diode circuit can be substituted by a single equivalent resistor.

Linear Small-Signal Equivalent Circuits

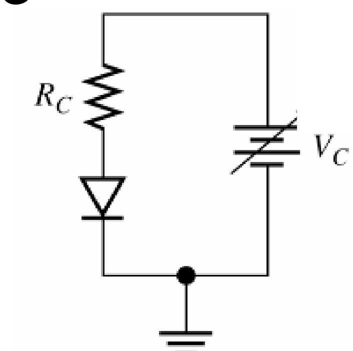
A diode in linear small-signal equivalent circuit is simplified to a resistor.

We first determine the operating point (Q point) by dc bias.



* When small ac signal injects, it swings the Q point slightly up and down.

* If the signal is small enough, the characteristic is straight.



$$\Delta i_D \cong \left(\frac{d\,i_D}{d\,v_D}\right)_Q \Delta v_D$$

Δi_D is the small change in diode current

Δv_D is the small change in diode voltage

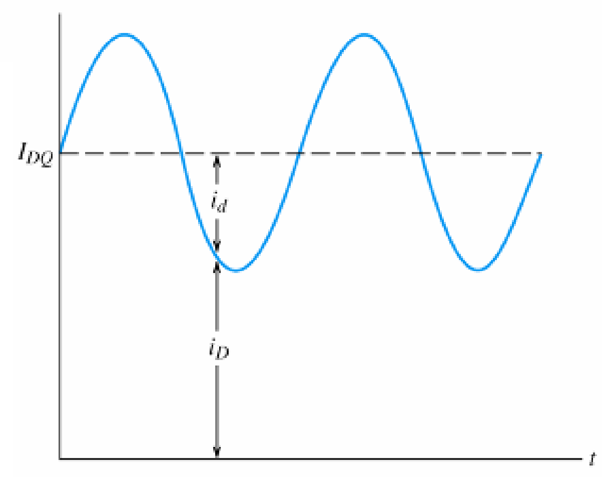


Illustration of diode currents.

Linear Small-Signal Equivalent Circuits

Define the dynamic resistance of the diode as:

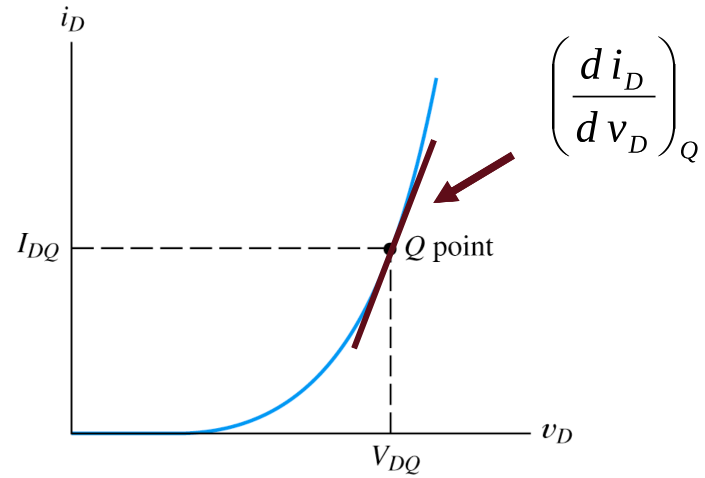
$$r_d \cong \left[\left(\frac{d\,i_D}{d\,v_D}\right)_Q\right]^{-1} \qquad \text{We will have:}$$

$$\Delta i_D \cong \left(\frac{d\,i_D}{d\,v_D}\right)_Q \Delta v_D \quad \Rightarrow \quad \Delta i_D \cong \frac{\Delta v_D}{r_d}$$

Replace Δi_D and Δv_D by i_d and v_d denoting small changes, we have for ac signals:

$$\boxed{i_d = \frac{v_d}{r_d}}$$

Furthermore, by applying the Shockley equation, we have: $\boxed{r_d = \frac{nV_T}{I_{DQ}}}$



Diode characteristic, illustrating the Q point

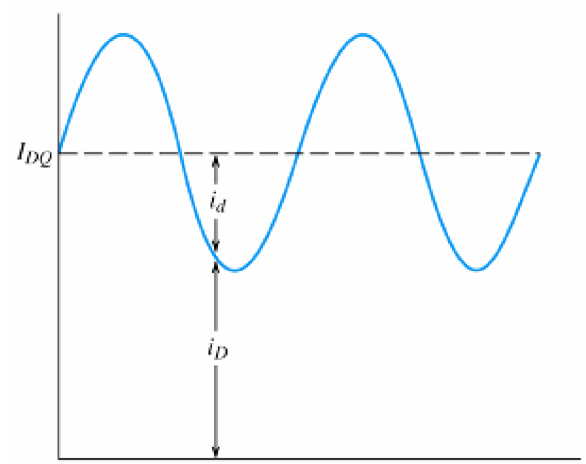


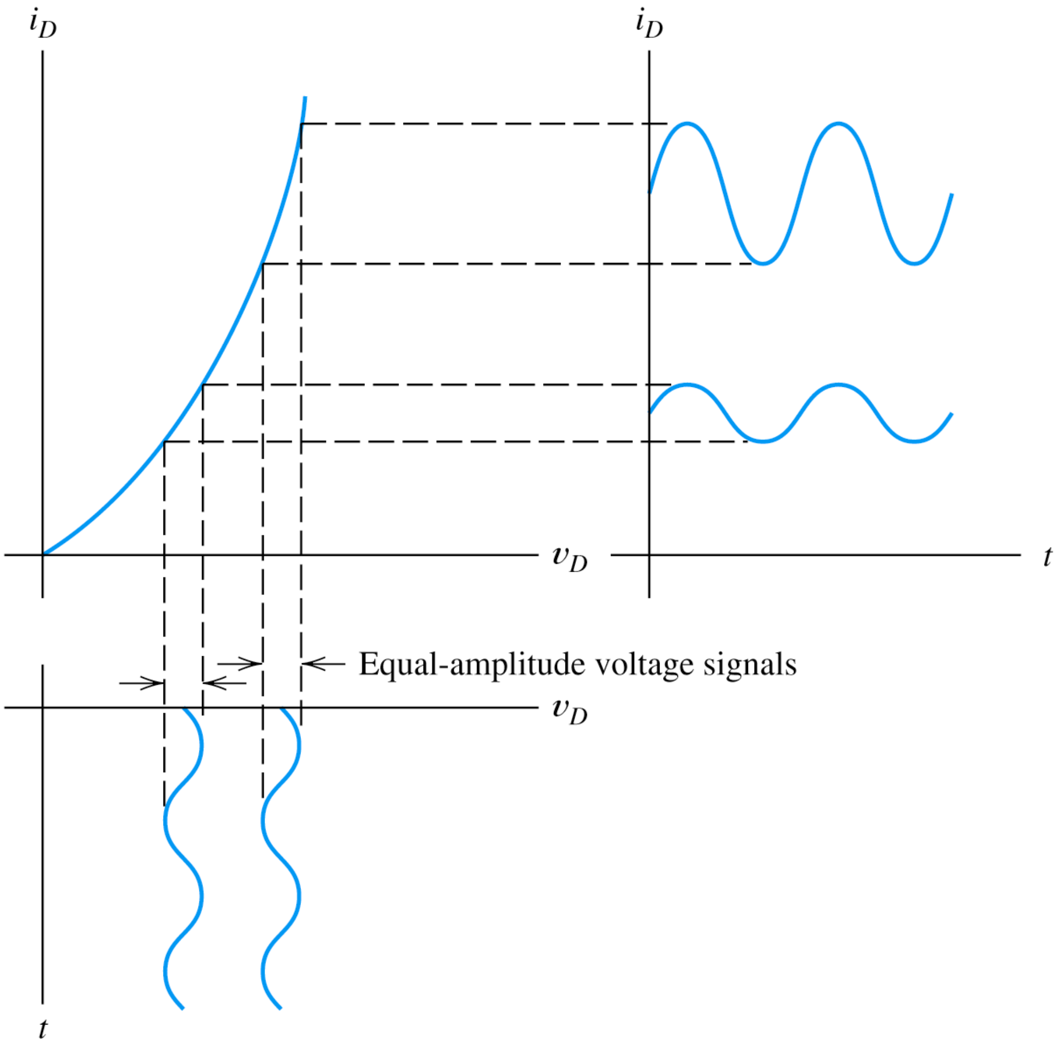
Illustration of diode currents.

Linear Small-Signal Equivalent Circuits

$$i_d = \frac{v_d}{r_d}, \quad r_d = \frac{nV_T}{I_{DQ}}$$

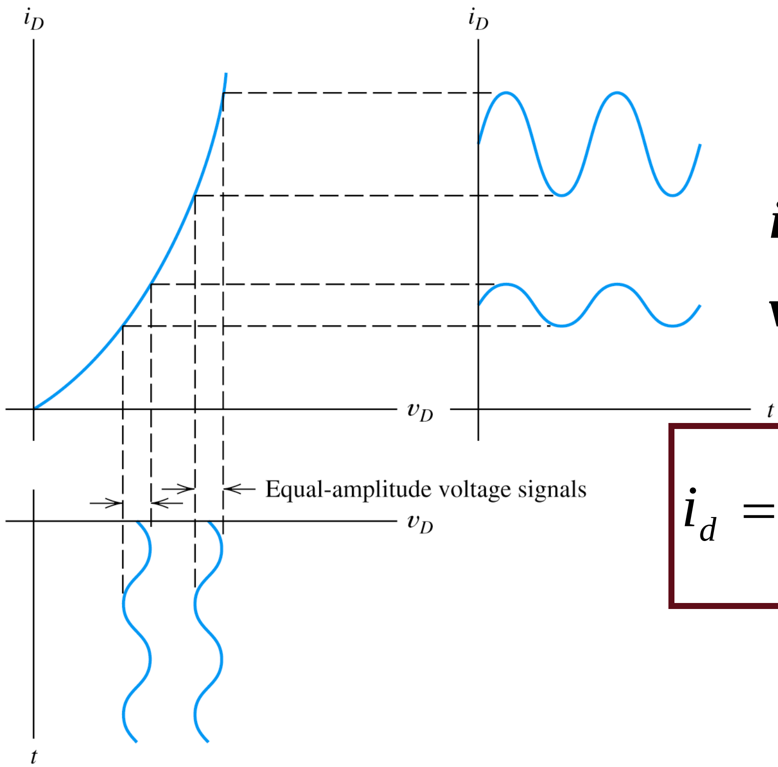
* By using these two equations, we can *treat diode simply as a linear resistor* in small ac signal analysis.

* Note: An ac voltage of fixed amplitude produces different ac current change at different Q point.



As the Q point moves higher, a fixed-amplitude ac voltage produces an ac current of larger amplitude.

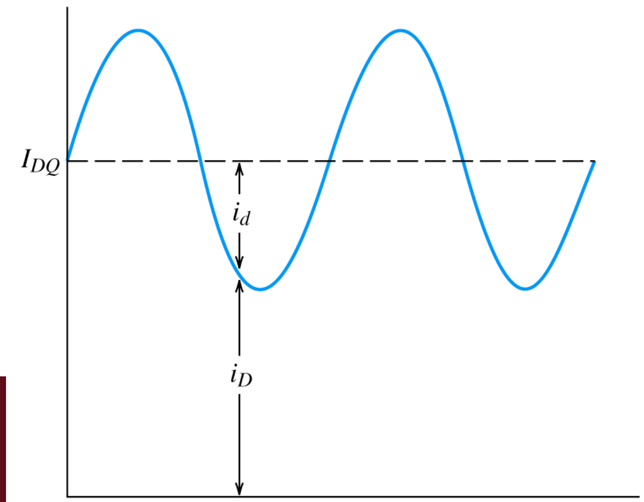
Linear Small-Signal Equivalent Circuits



$$i_D = I_{DQ} + i_d$$

$$v_D = V_{DQ} + v_d$$

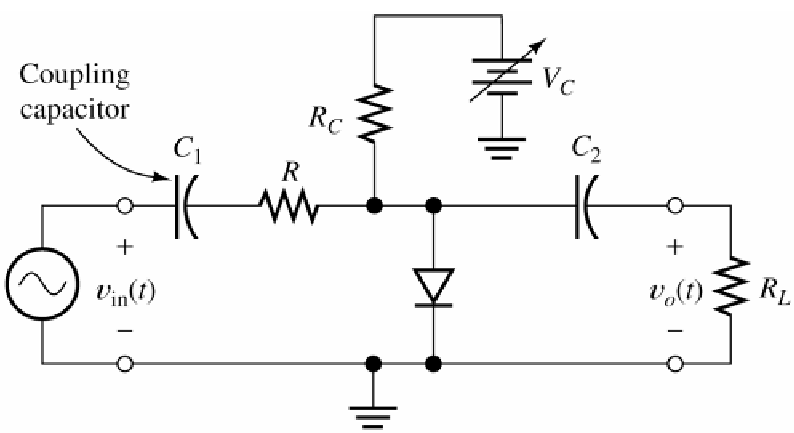
$$\boxed{i_d = \frac{v_d}{r_d}, \quad r_d = \frac{nV_T}{I_{DQ}}}$$



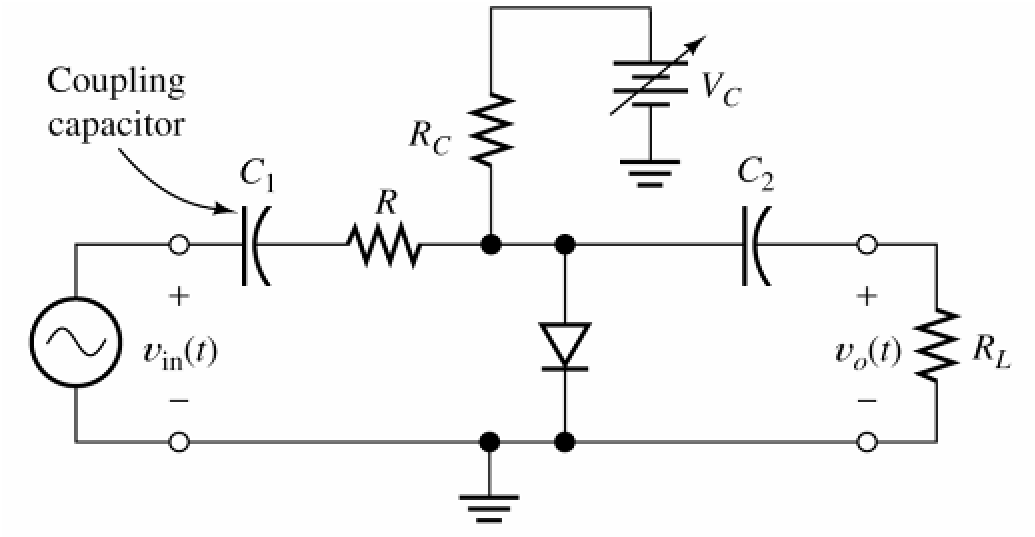
(1) V_{DQ} and I_{DQ} represent the dc signals at the Q point.

(2) v_d and i_d represent the small sc signals.

(3) v_D and i_D represent the total instantaneous diode voltage and current.



Voltage-Controlled Attenuator

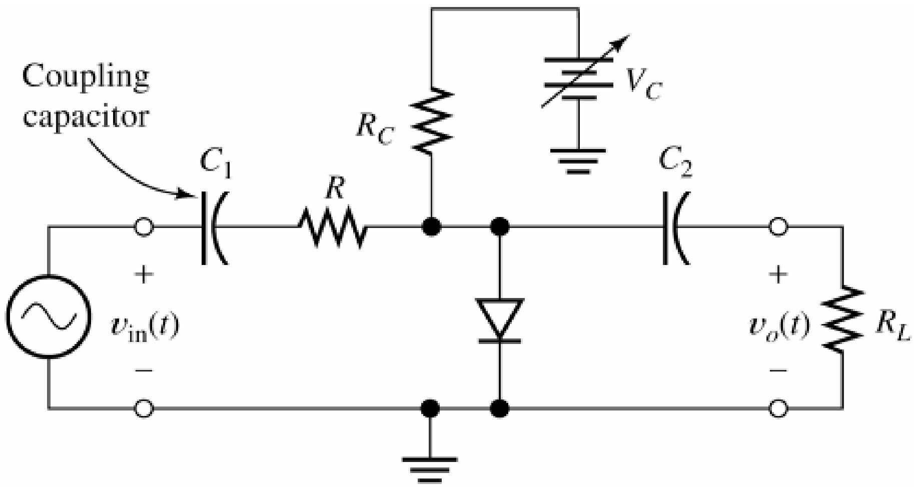


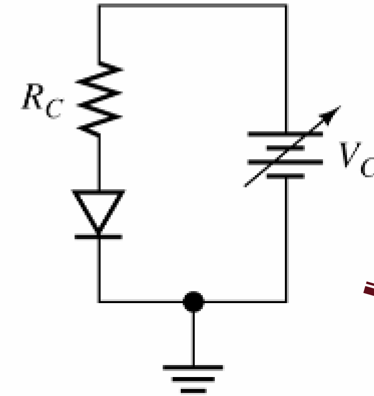
* The function of this circuit is to produce an output signal that is a variable fraction of the ac input signal.

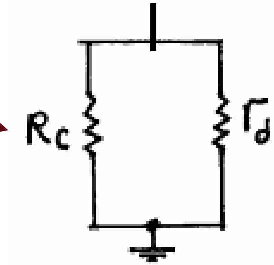
* Two large *coupling capacitors*: behave like short circuit for ac signal and open circuit for dc, thus the Q point of the diode is unaffected by the ac input and the load.

$$Z_C = \frac{1}{j\omega C}$$

Voltage-Controlled Attenuator

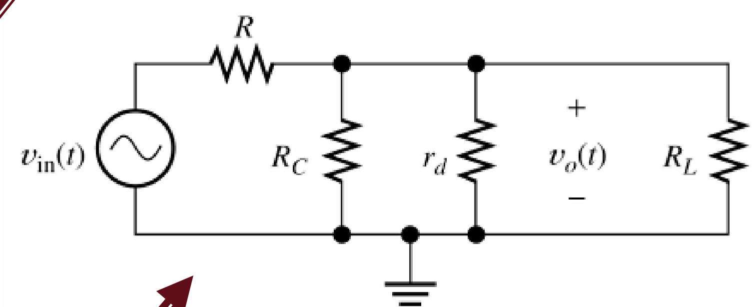






First apply dc analysis to find the diode Q point,

determine I_{DQ}*, then the* r_d *of the diode:* $r_d = \dfrac{nV_T}{I_{DQ}}$

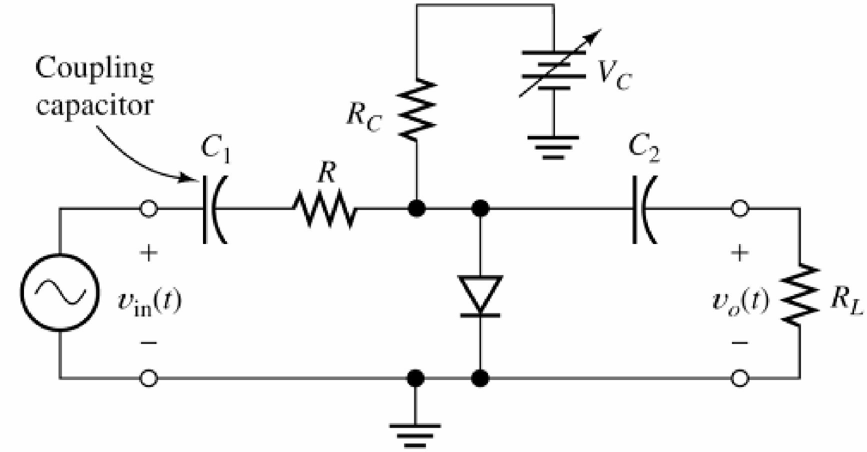


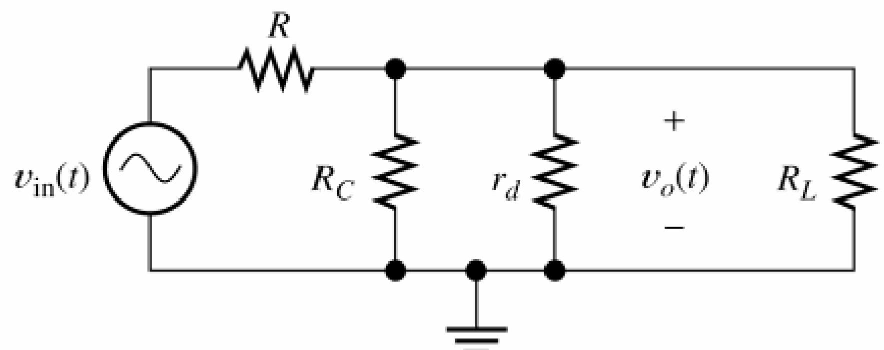
Next, we perform small ac signal analysis:

(note: the dc voltage source has an ac component of current but no ac voltage, the dc voltage source is equivalent to a short circuit for ac signal.)

$$R_p = \frac{1}{1/R_C + 1/R_L + 1/r_d}, \text{ based on voltage divider: } \boxed{A_v = \frac{v_o}{v_{in}} = \frac{R_p}{R + R_p} < 1}$$

Exercise - Voltage-Controlled Attenuator

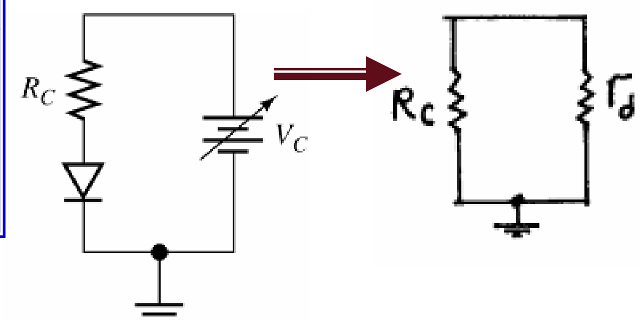




$$\text{Given}: R = 100\Omega,\ R_C = R_L = 2k\Omega,\ \text{diode } n = 1 \text{ at } 300K$$

$$\text{Find}: \text{the Q - point values assuming } V_f = 0.6V$$

$$\text{and } A_v \text{ for } V_C = 1.6 \text{ and } 10.6V$$



First apply dc analysis to find the diode Q point,

$$I_{DQ} = \frac{V_C - 0.6}{R_C},\quad r_d = \frac{nV_T}{I_{DQ}} \quad \text{with } V_T = 0.026V$$

Next, we perform small ac signal analysis:

$$R_p = \frac{1}{1/R_C + 1/R_L + 1/r_d},\quad A_v = \frac{v_o}{v_{in}} = \frac{R_p}{R + R_p}$$

Evaluating we have

V_C (V)	1.6	10.6
I_{DQ} (mA)	0.5	5.0
r_d (Ω)	52	5.2
R_p (Ω)	49.43	5.173
A_v	0.3308	0.04919