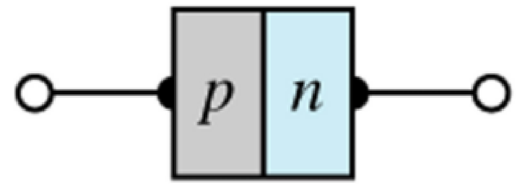
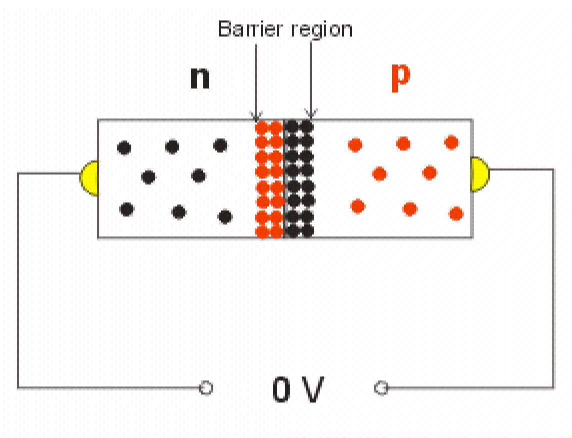
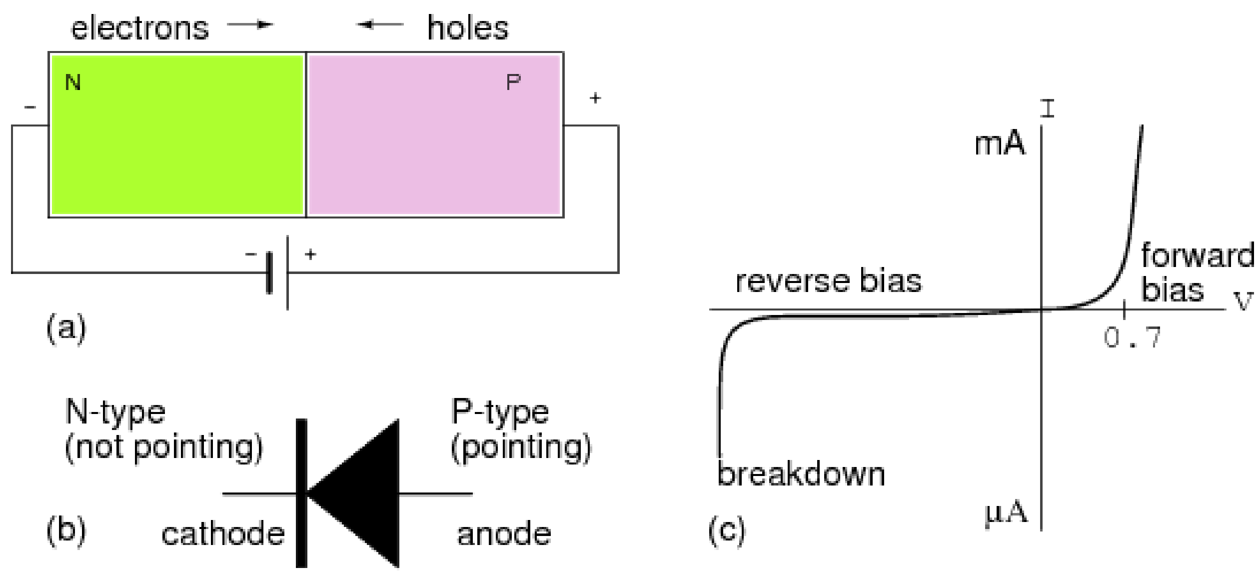
Diodes



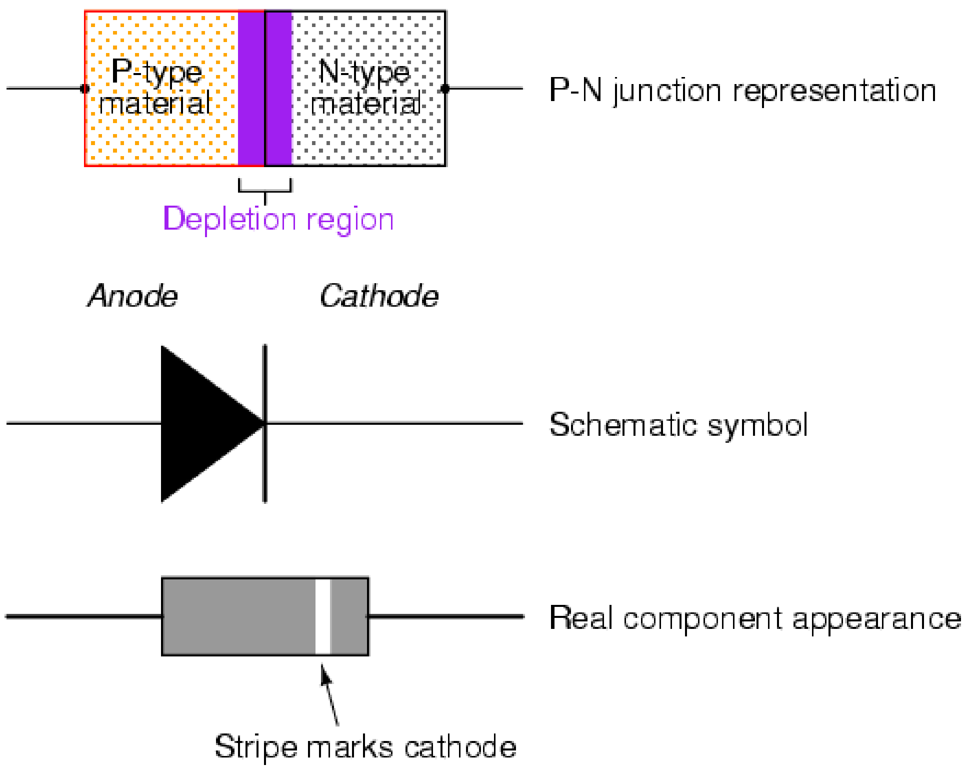


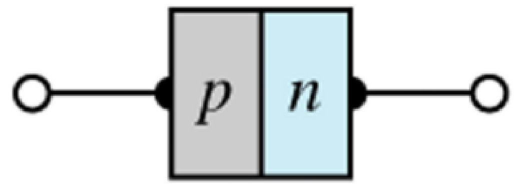
Diode with no bias



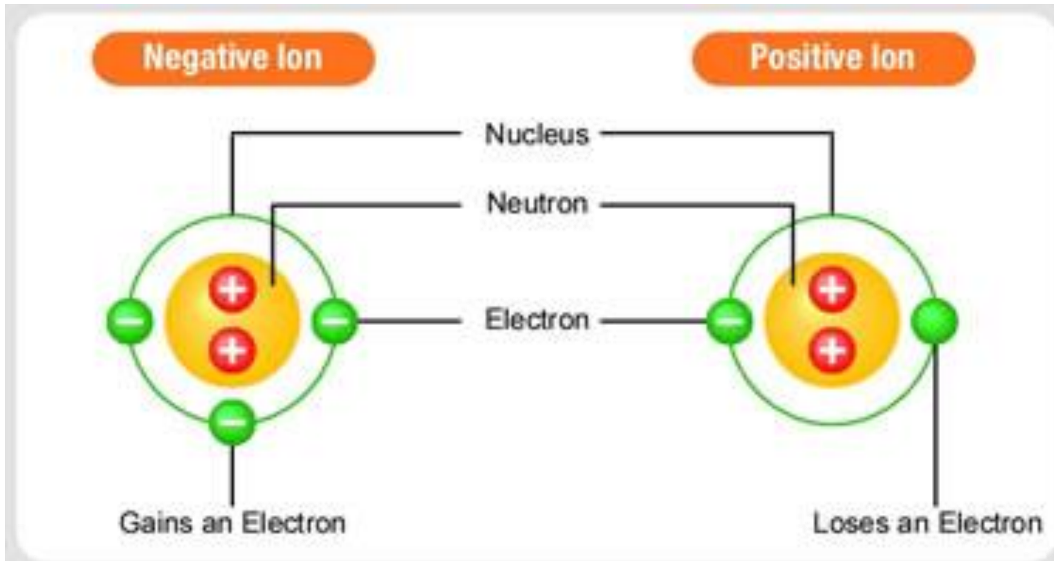
Diode

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





Negative and Positive Ions

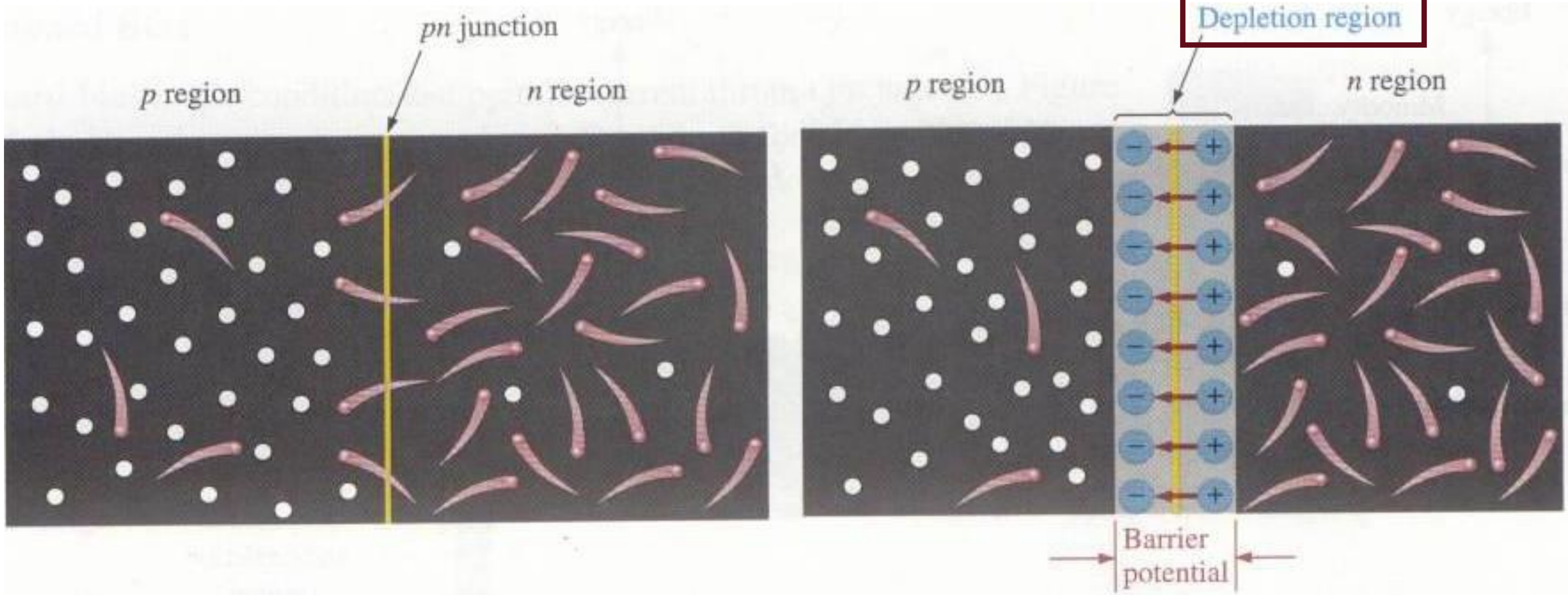


The PN-Junction

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.

This depletion region becomes an insulating layer.

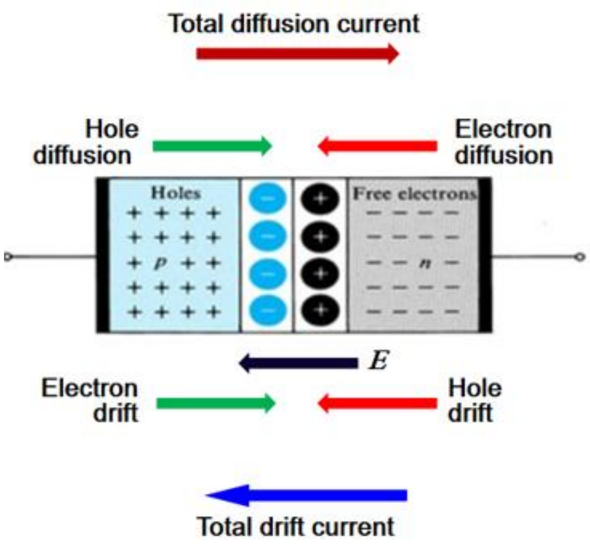


(a) At the instant of junction formation, free electrons in the *n* region near the *pn* junction begin to diffuse across the junction and fall into holes near the junction in the *p* region.

(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.

Current Flow Across Junction: Equilibrium

At equilibrium in a p-n junction, the forward diffusion current in the depletion region is balanced with a reverse drift current, **so that the net current is zero.**



-The process of diffusion continues until the depletion region expands to a width such that the electric field in the depletion region is large enough so that the diffusion current due to majority carriers is exactly balanced by the drift current due to minority carrier.

drift current density

diffusion current density

$$q\mu_p pE = -qD_p \frac{dp}{dx}$$

$$V_B = \frac{kT}{q} \ln \frac{N_A N_D}{{n_i}^2}$$

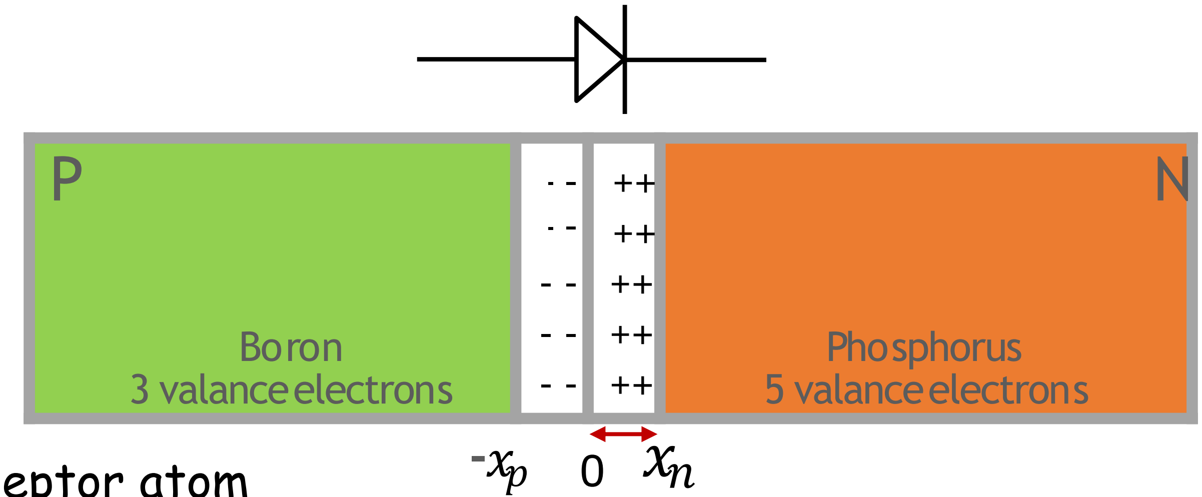
Number acceptor atoms

Number donor atoms

Free electrons in intrinsic silicon

Barrier potential

Depletion Region



acceptor atom concentration

$$x_p N_A = x_n N_D$$

$$W = x_p + x_n$$

donor atom concentration

Barrier potential

$$W = \sqrt{\frac{2.\varepsilon_o.\varepsilon_r.V_B}{q}\left[\frac{1}{N_D} + \frac{1}{N_A}\right]}$$

Width of unbiased depletion region

ε_r: Relative dielectric permittivity of semiconductor material

In the depletion region of a pn junction, there is a shortage of.

a) Acceptor ions

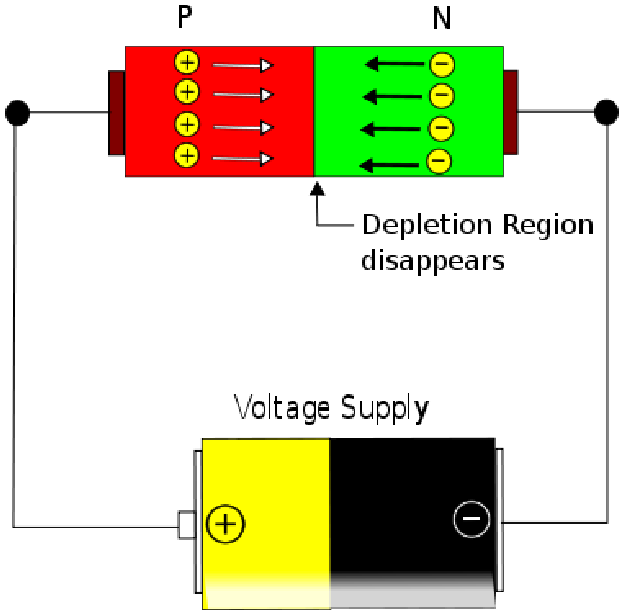
b) Holes and free electrons

c) Donor ions

d) Atoms

e) None of the above

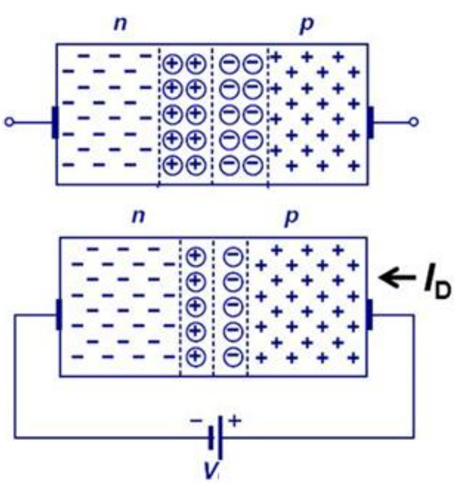
Forward Bias



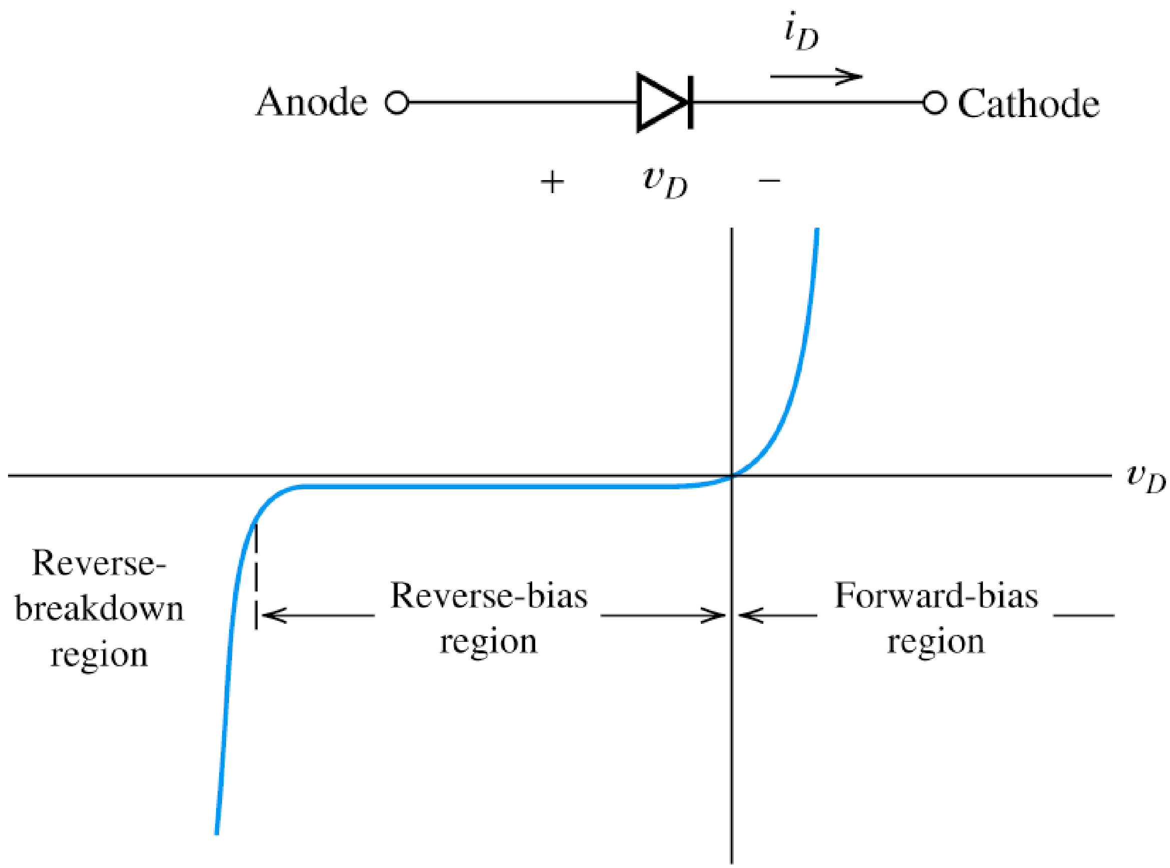
In forward bias the P-Region of the diode is connected with the positive terminal of the battery and N-region is connected with the negative region.

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.

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.

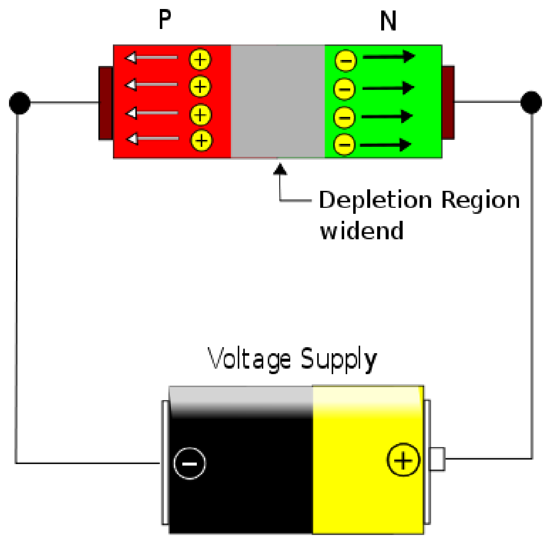


Forward Bias

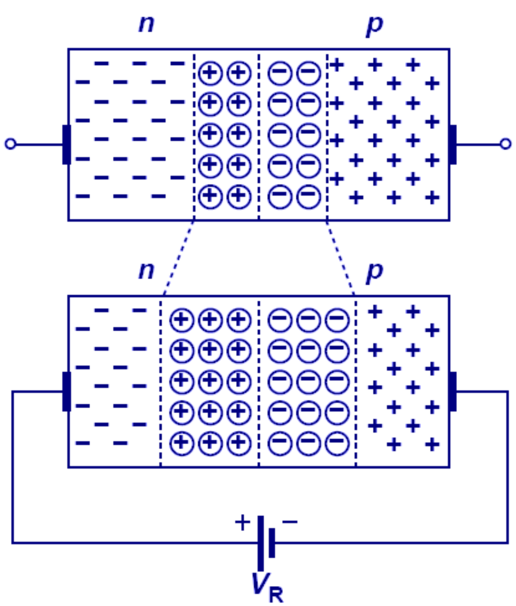


At one particular voltage level (V_f called as threshold / cut-off voltage) the depletion layer disappears. From this point the diode starts to conduct very easily and the diode current increases exponentially to the voltage applied.

Reverse Bias



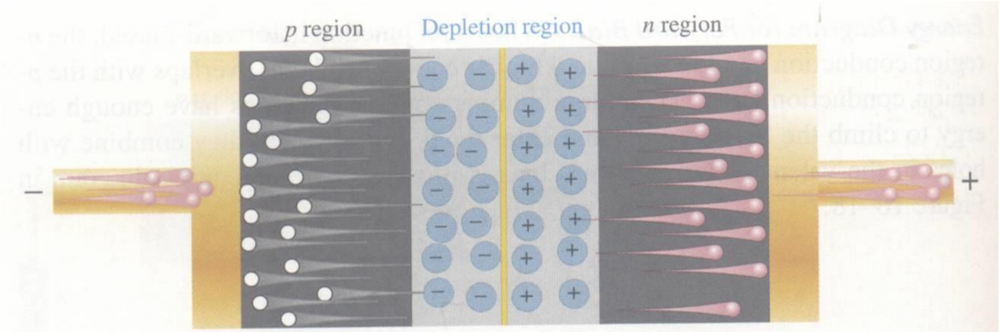
In reverse bias the P-type region is connected to negative voltage and N-type is connected to positive terminal as shown above.



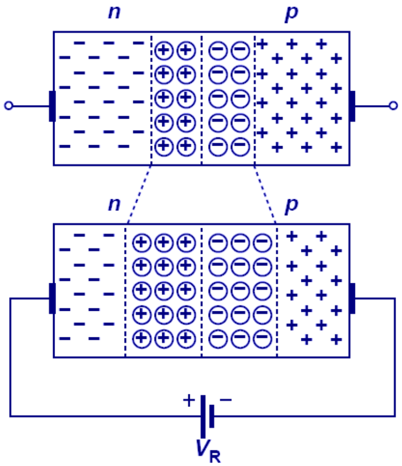
The electrons in N-type material is sucked out of the diode by the positive terminal of the battery. So initially the depletion layer widens (see image above) and it occupies the entire diode. The resistance offered by the diode is very huge.

Reverse Bias

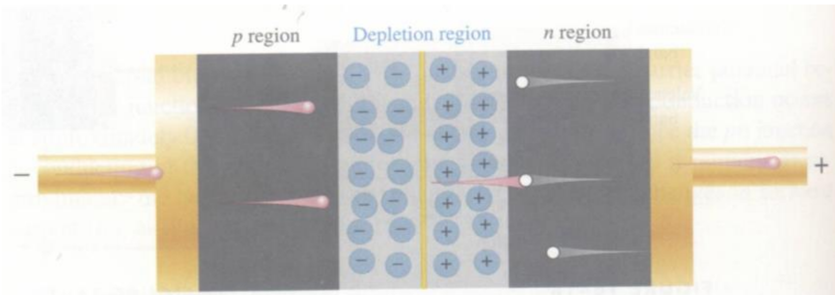
Negative terminal of the DC voltage source is connected to the p region and positive terminal of the DC voltage source to the n region. **Depletion region widens until its potential difference equals the bias voltage.**



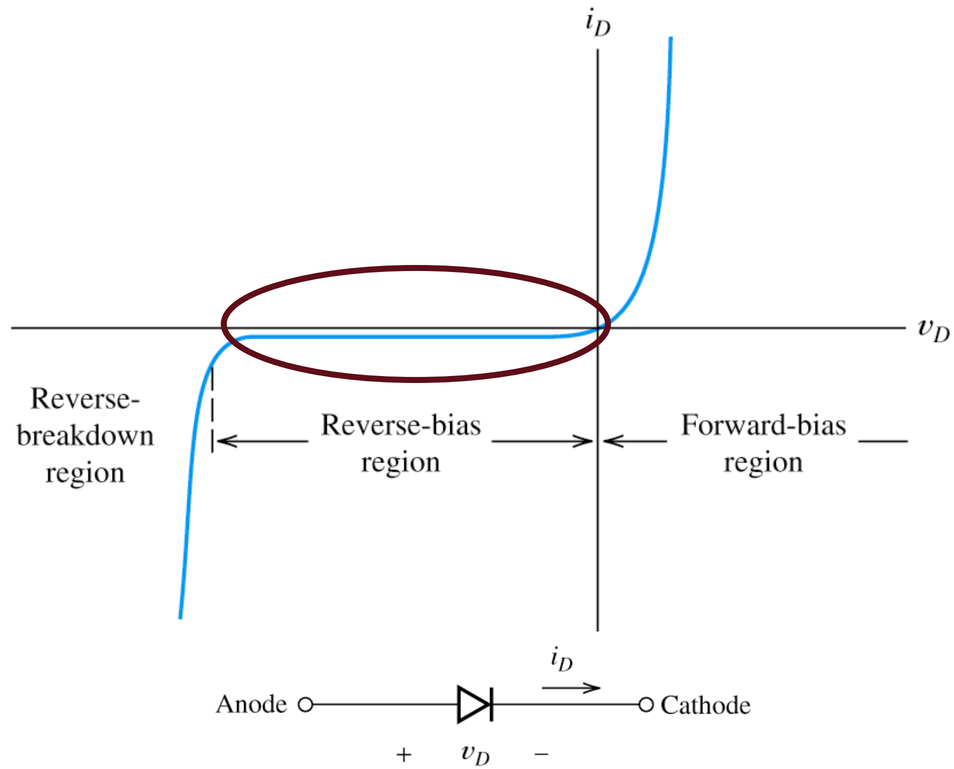
(a) There is transient current as depletion region widens.



Reverse Bias



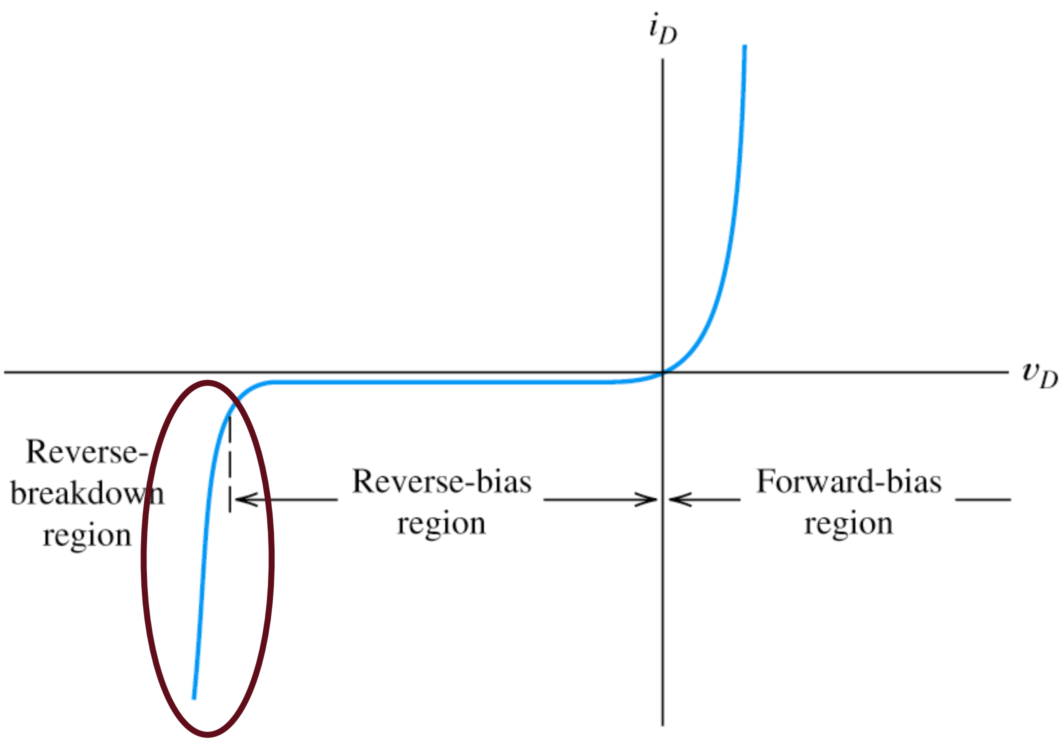
(b) Majority current ceases when barrier potential equals bias voltage. There is an extremely small reverse current due to minority carriers.



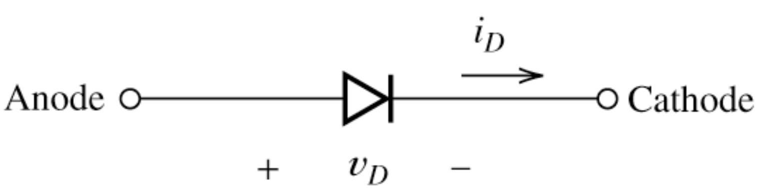
The current that flows in reverse bias is only due to minority charge which is in nano amperes in silicon and micro amperes in high power silicon and germanium diodes.

Reverse Breakdown

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



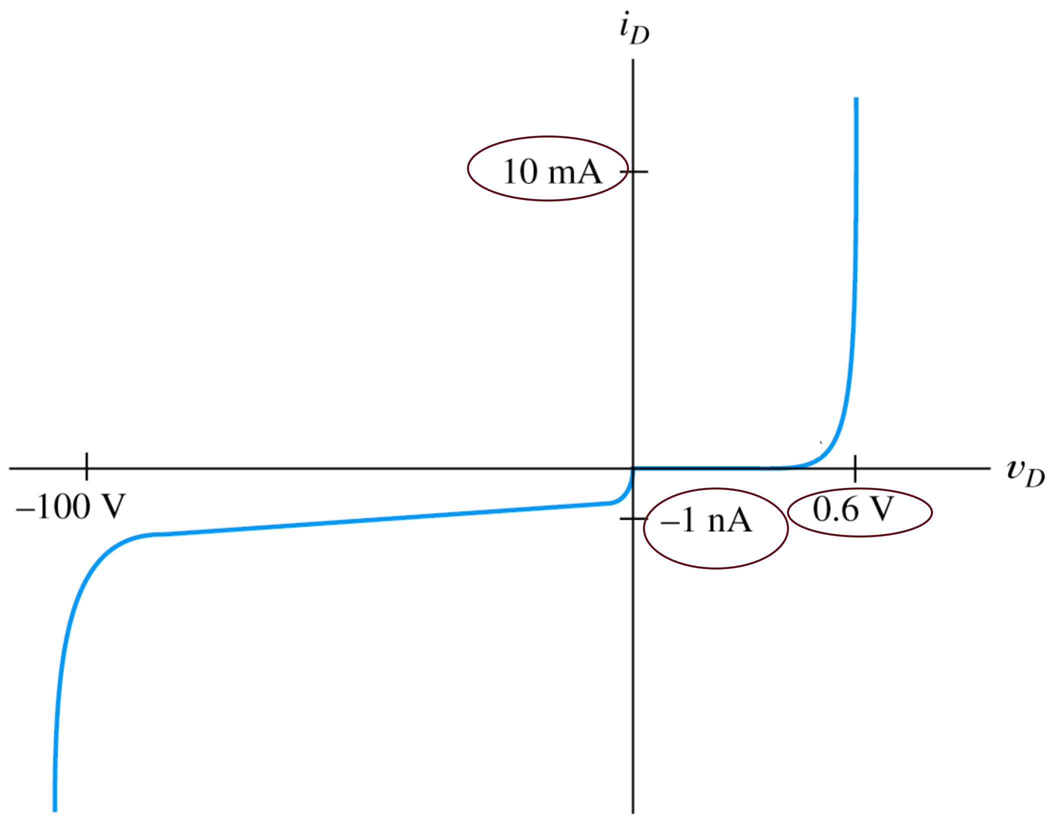
(b) Volt–ampere characteristic



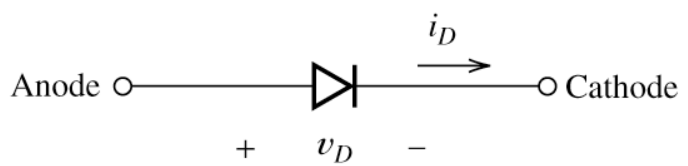
If the reverse voltage is made high enough, then the junction will break down

and almost all electrons will flow from anode to cathode.

The Diode Characteristic I-V Curve

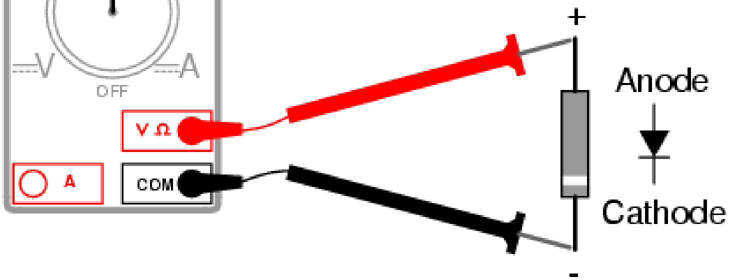


Volt–ampere characteristic for a typical small-signal silicon diode at a temperature of 300 K. Notice the change of scale for negative current and voltage.

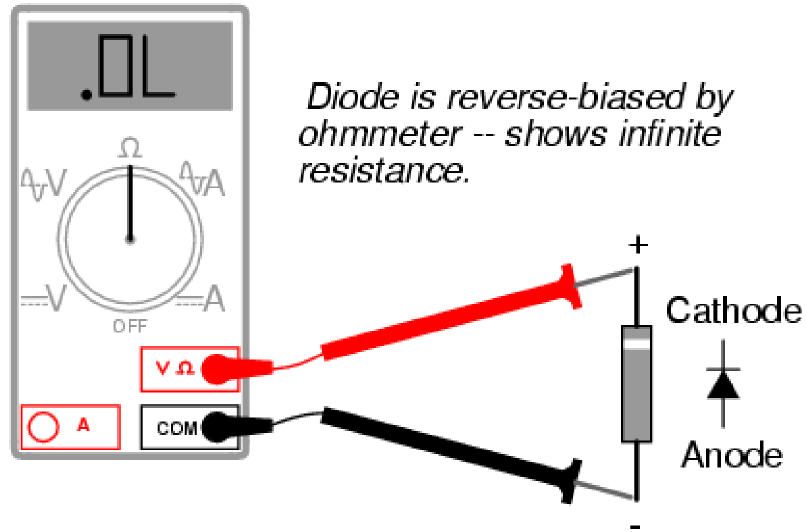


Diode – Characteristic

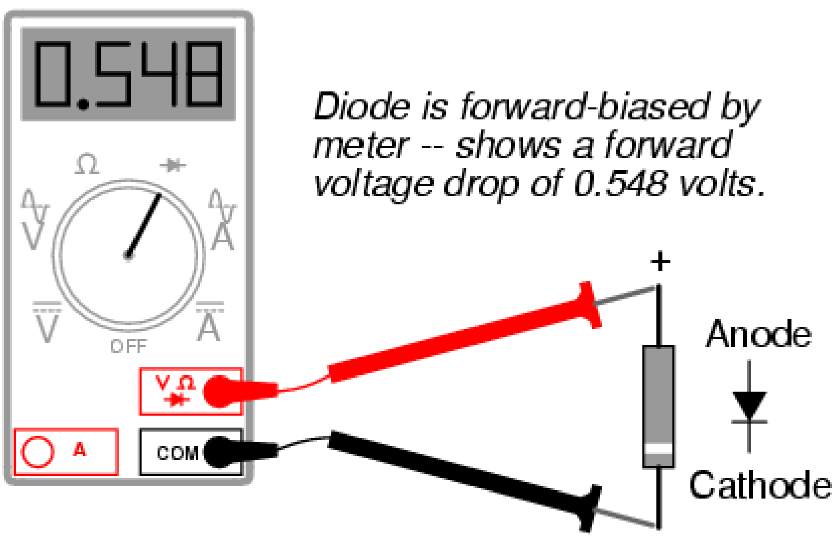
Diode is forward-biased by ohmmeter -- shows 0 ohms of resistance.

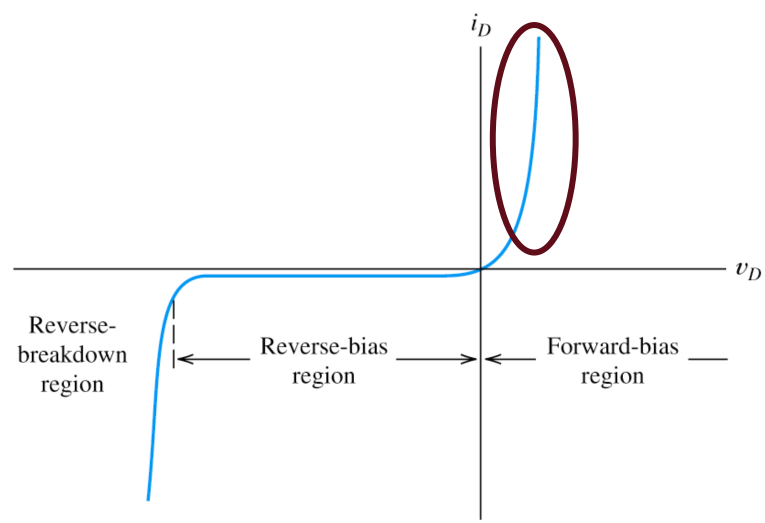


Diode is reverse-biased by ohmmeter -- shows infinite resistance.

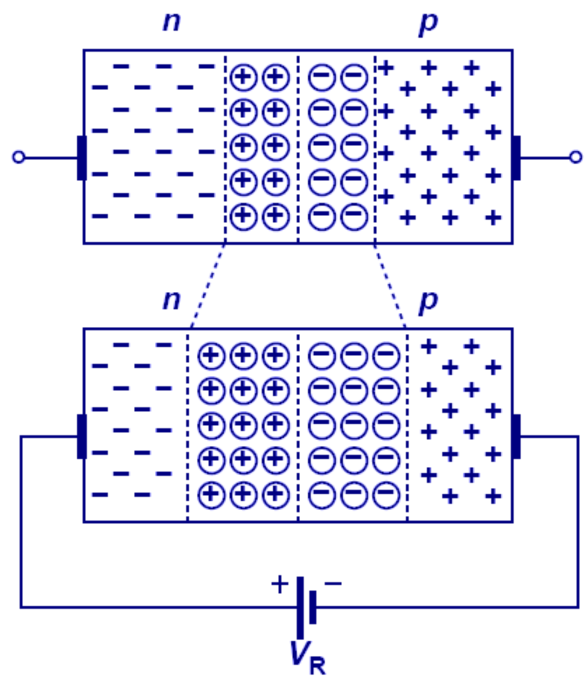


Diode is forward-biased by meter -- shows a forward voltage drop of 0.548 volts.



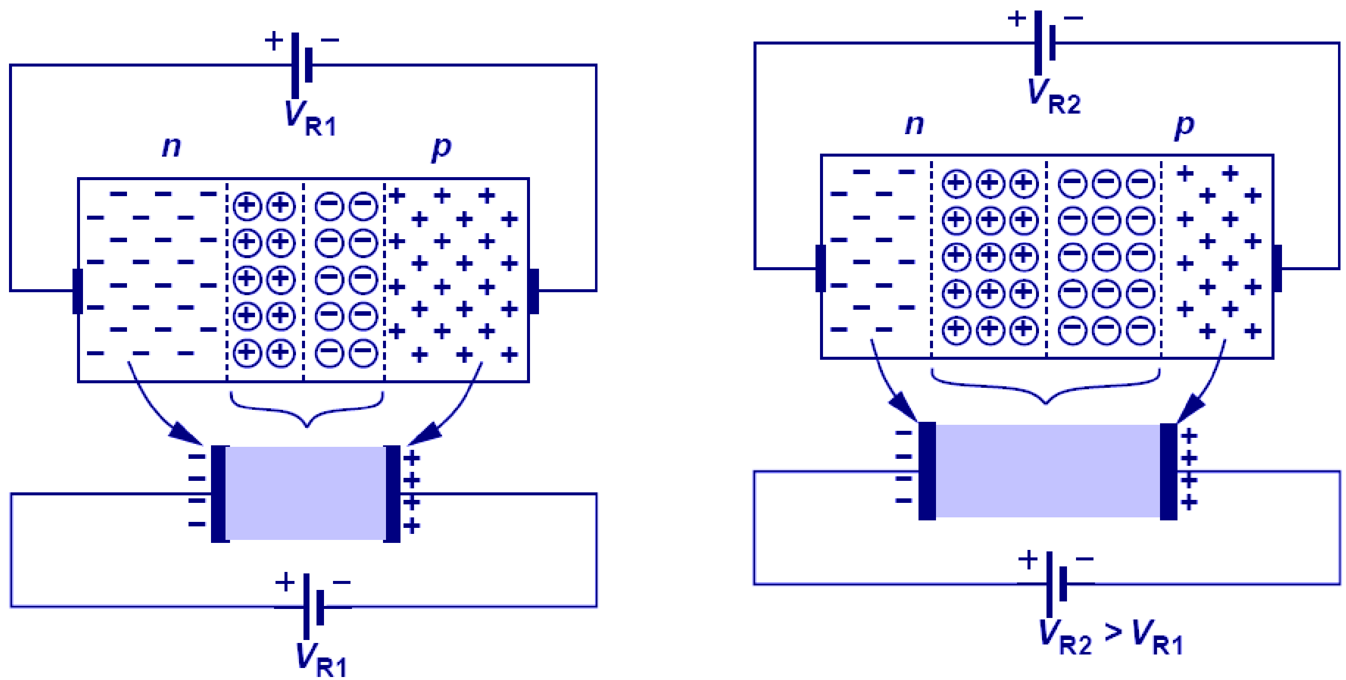


Diode in Reverse Bias



When the N-type region of a diode is connected to a higher potential than the P-type region, the diode is under reverse bias, which results in **wider depletion region and larger built-in electric field** across the junction.

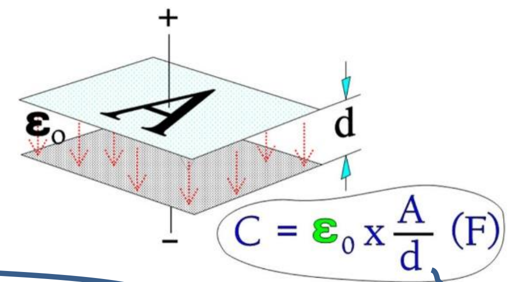
Reverse Biased Diode's Application: Voltage-Dependent Capacitor



(a) (b)

The PN junction can be viewed as a capacitor. By varying V_R, the depletion width changes, changing its capacitance value; therefore, reversed biased PN junction is actually a voltage-dependent capacitor.

Voltage-Dependent Capacitance

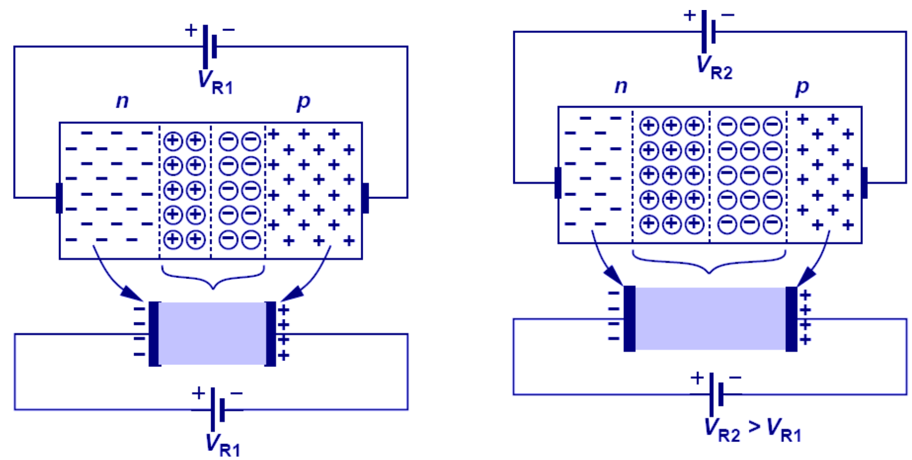


$C_j = \varepsilon_{si}\, A/W_{dep}$

W_{dep}: Width of depletion region

A: Cross-sectional area of PN junction

ε_{si}: Dielectric permittivity of semiconductor material



(a) (b)

PN Junction under Reverse Bias

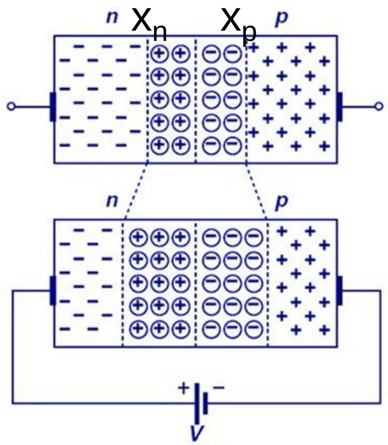
- A reverse bias increases the potential drop across the junction. As a result, the magnitude of the electric field increases and the width of the depletion region widens.

$$\boxed{W_{dep} = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_B+V)}}$$

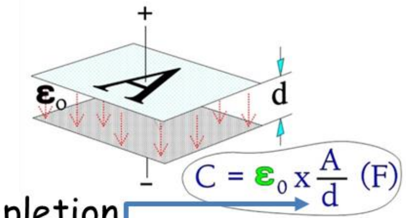
$$x_p = \sqrt{\frac{2\varepsilon(V_B+V)}{qN_A[1+(N_A/N_D)]}}$$

$$x_n = \sqrt{\frac{2\varepsilon(V_B+V)}{qN_D[1+(N_D/N_A)]}}$$

$$W_{\text{dep}} = x_p + x_n$$



$C_j = \varepsilon_{si}\, A/W_{dep}$



W_{dep}: Width of depletion region (d)

A: Cross-sectional area of PN junction

ε_{si}: Dielectric permittivity of semiconductor material

PN Junction under Forward Bias

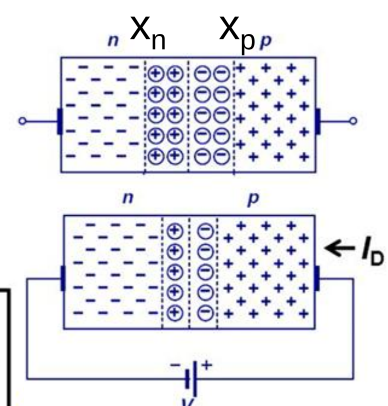
- A forward bias decreases the potential drop across the junction. As a result, the magnitude of the electric field decreases and the width of the depletion region narrows.

$$x_p = \sqrt{\frac{2\varepsilon(V_B-V)}{qN_A[1+(N_A/N_D)]}}$$

$$x_n = \sqrt{\frac{2\varepsilon(V_B-V)}{qN_D[1+(N_D/N_A)]}}$$

$$W_{\text{dep}} = x_p + x_n$$

$$\boxed{W_{dep} = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_B-V)}}$$



Shockley Equation

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

Geometry, doping and material constants are lumped in I_s

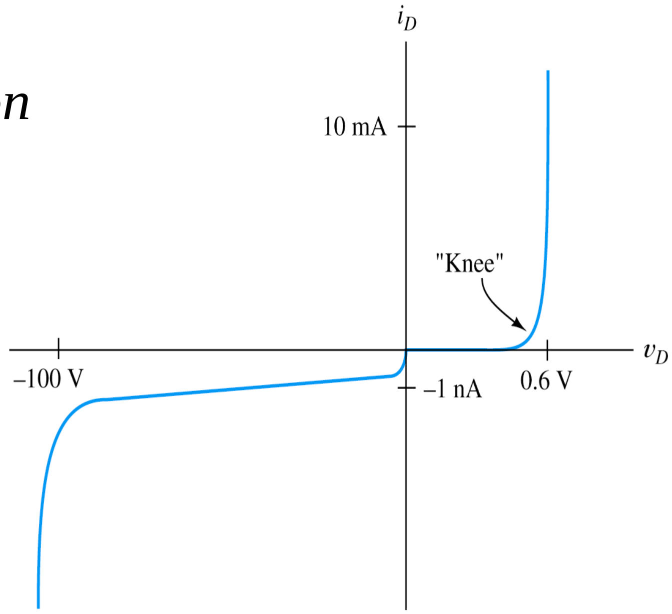
$where\ I_s \cong 10^{-14}\ A\ at\ 300K\ is\ the\ (reverse)\ saturation$ $current,\ n \cong 1\ to\ 2\ is\ the\ emission\ coefficient,$

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

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

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

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



Saturation Current Calculation

Diffusion constants

$$D_n = V_T \, \mu_n$$
$$D_p = VT \, \mu_p$$

$$I = Aq\left(\frac{D_p}{L_p} p_{n0} + \frac{D_n}{L_n} n_{p0}\right)\left(e^{V/V_T} - 1\right)$$

$$I = I_S\left(e^{V/V_T} - 1\right) \longleftarrow$$ PN junction current

$$I_S = Aqn_i^2\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right) \longleftarrow$$ Saturation current

V: Applied forward bias voltage

$D_{p,n}$: Diffusion constants

n_i: Free electrons in intrinsic semiconductor material

A: Cross sectional area of PN junction

L_p: Diffusion length of holes in the n material.

L_n: Diffusion length of electrons holes in the p material.
$N_{A,D}$: Number of acceptor (donor) atoms

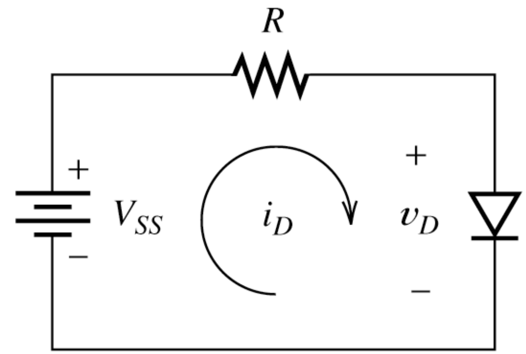
Diffusion length is the average **length** of a carrier moves between generation and recombination. Semiconductor **materials** that are heavily doped have greater recombination rates and consequently, have shorter **diffusion lengths**.

Load-Line Analysis of Diode Circuit

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

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

It is difficult to write KCL or KVL equations.



For the circuit shown,

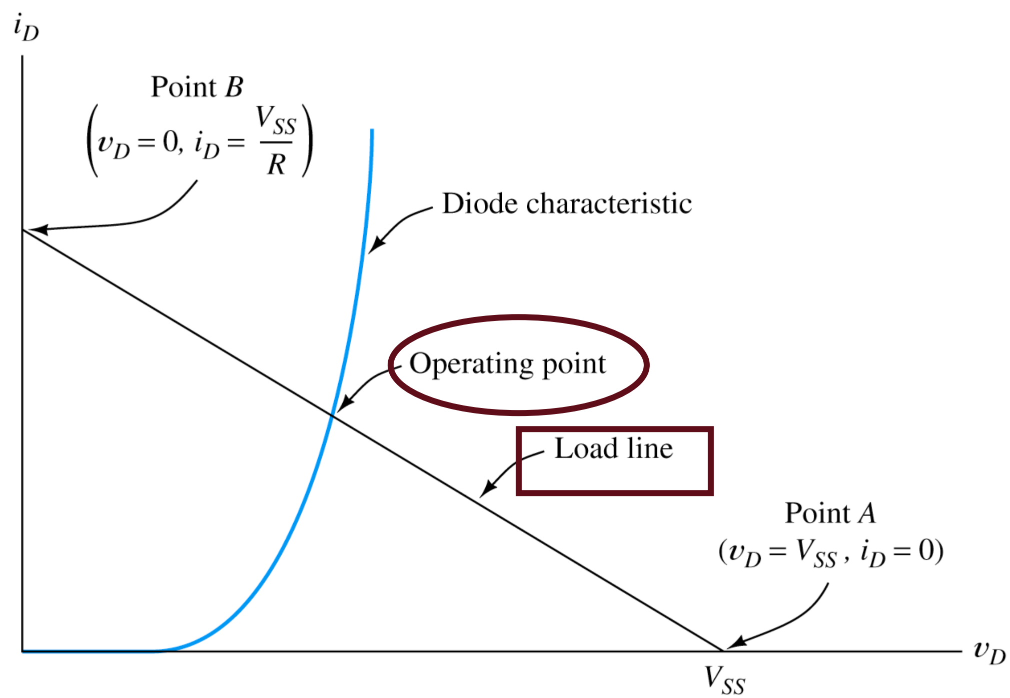
KVL gives:

$$\boxed{V_{SS} = R i_D + v_D}$$

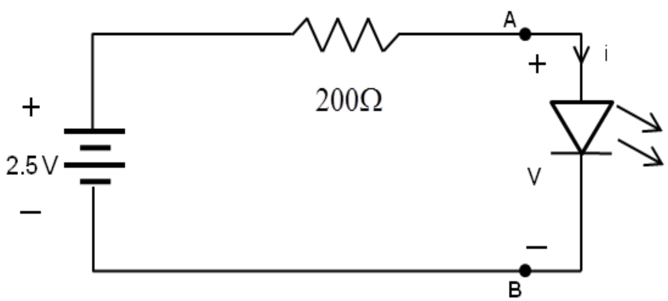
If the I-V curve of the diode is given,

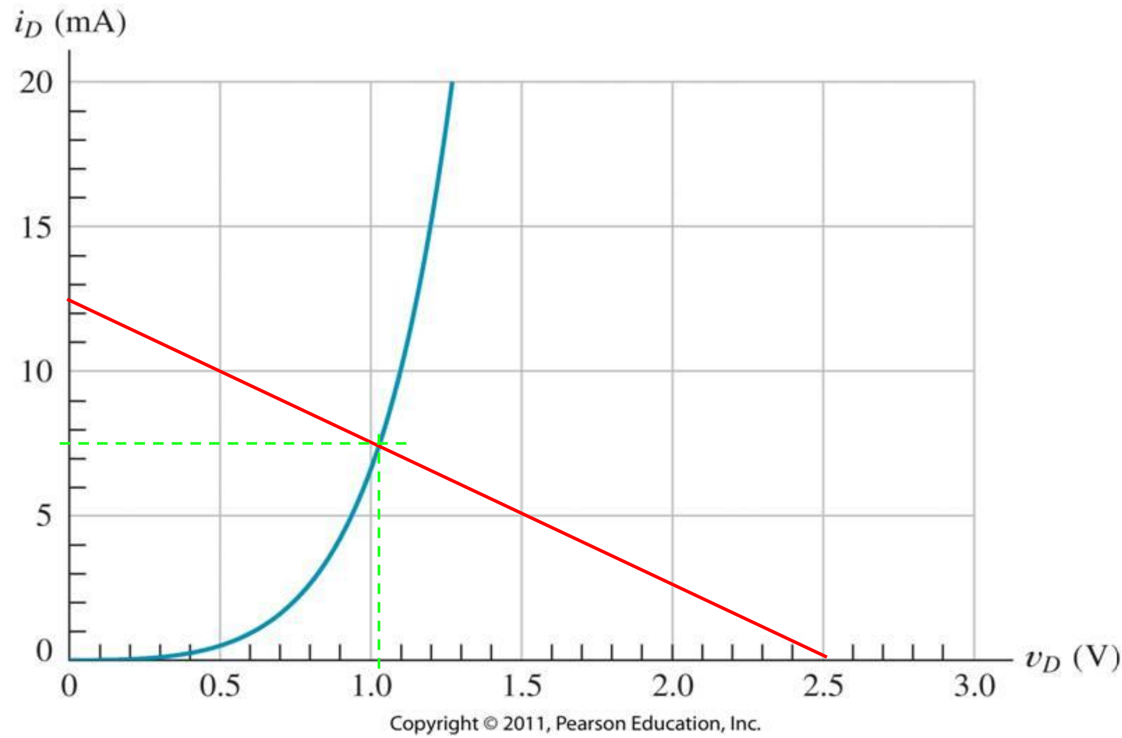
we can perform the

"Load-Line Analysis"



Find the current *i* and the voltage *v* across LED diode in the circuit. Assume that the diode characteristic is given on Figure right below.





Determine the load line

Step 1: Find i_D if $v_D = 0$ V (short circuit)

$$i_D = \frac{2.5}{200} = 12.5\ mA$$

Step 2: Find v_D if $i_D = 0$ A (open circuit)

$$v_D = 2.5\ V$$

Draw load line. Intersection of load line and diode characteristic is the *i* and *v* across LED diode: $v \approx 1.02$ V and $i \approx 7.5$ mA.

Example Load-Line Analysis

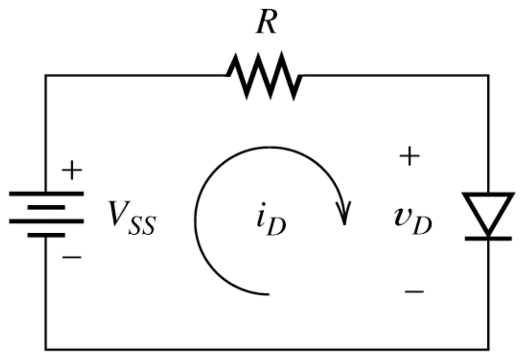
For the circuit shown,

Given : $V_{SS} = 2V, R = 1k\Omega,$

the I-V curve of the diode

Find : the diode current and voltage

at the operating point (Q-point)



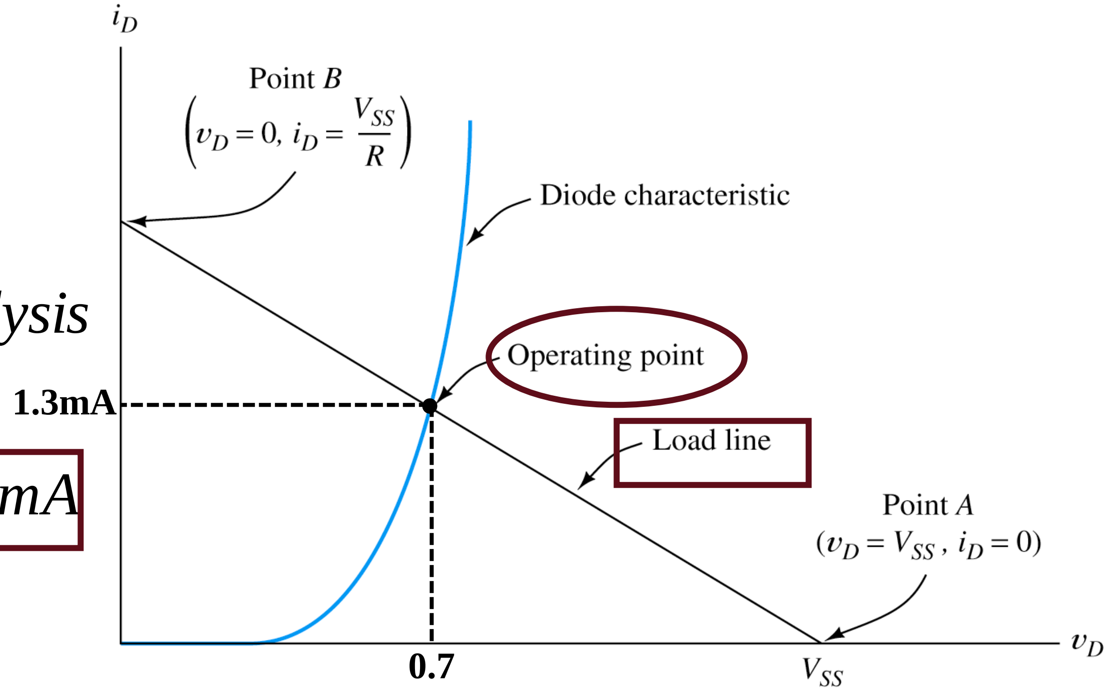
$$V_{SS} = R i_D + v_D, \text{ i.e.,}$$

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

$\Rightarrow$ perform load-line analysis

$\Rightarrow$ at the operating point

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

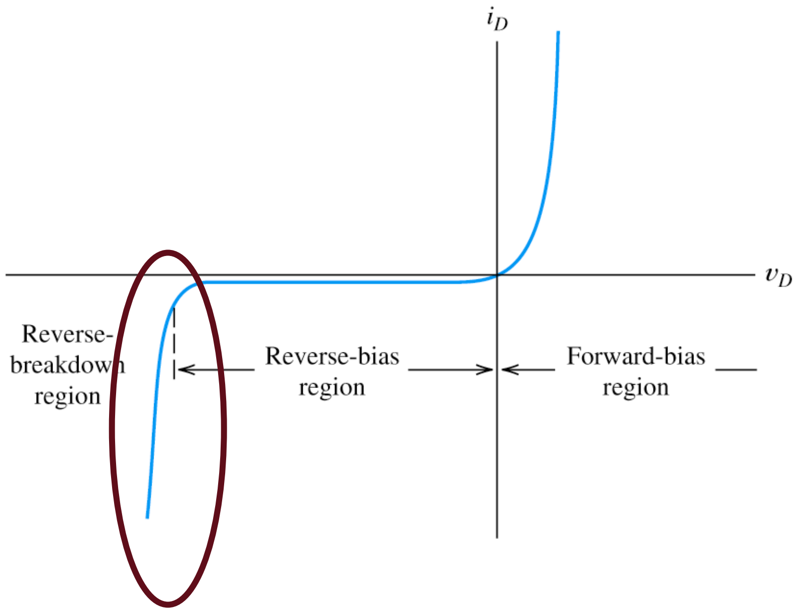


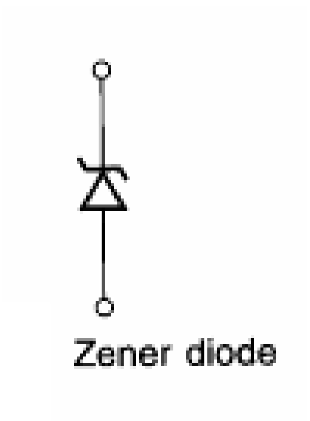
The Zener Diode

* *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 voltage that is stable despite changes in input voltage.



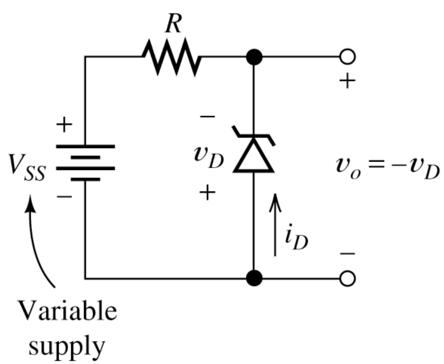


Zener-Diode Voltage-Regulator Circuits

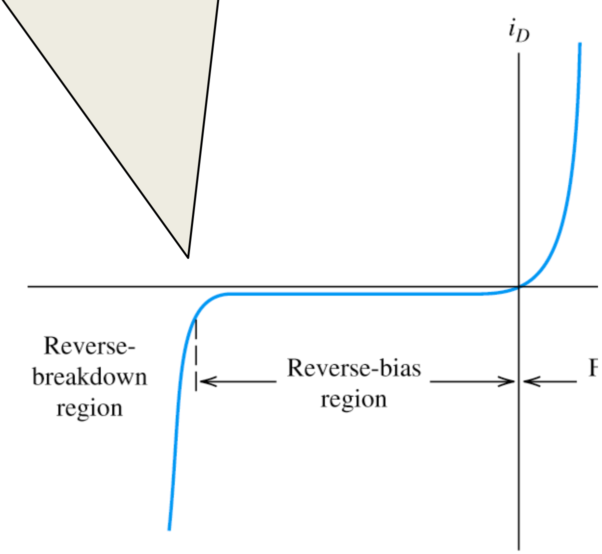
Sometimes, a constant output voltage while operating from a variable supply voltage is needed. Such circuits are called *voltage regulator*.

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.

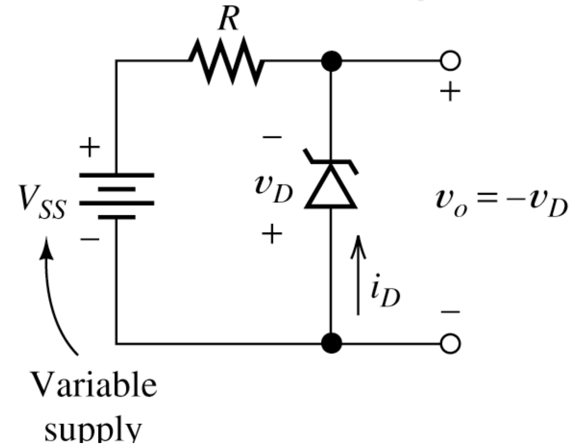


A simple regulator circuit that provides a nearly constant output voltage v_o from a variable supply voltage.



Zener-Diode Voltage-Regulator Circuits (Example)

$$\boxed{\begin{array}{l} \textit{Given: the Zener diode I-V curve, } R = 1k\Omega \\ \textit{Find: the output voltage for } V_{SS} = 15\,V \textit{ and} \\ \qquad\qquad\qquad\qquad\qquad V_{SS} = 20\,V \end{array}}$$



KVL gives the load line:

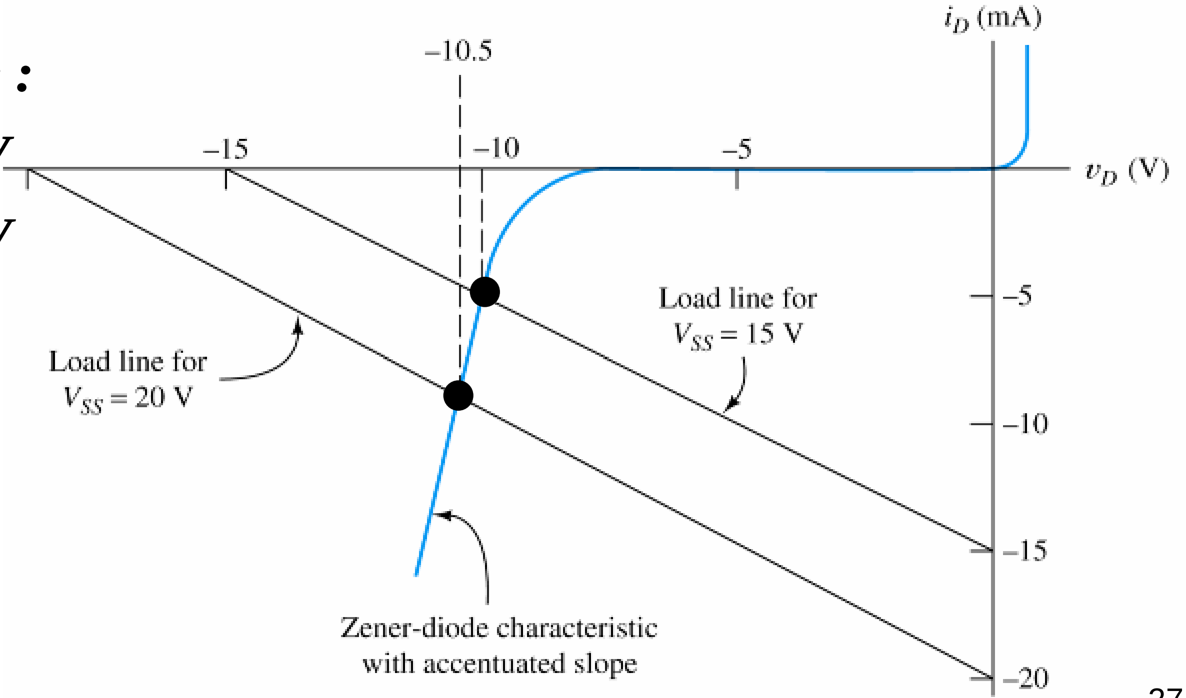
$$\boldsymbol{V_{SS} + R\,i_D + v_D = 0}$$

From the Q - point we have:

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

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

$$\boxed{\begin{array}{l} \textit{5V change in input} \\ \Rightarrow \textit{0.5V change in } v_o \end{array}}$$



Actual Zener diode performs much better!

Ideal-Diode Model

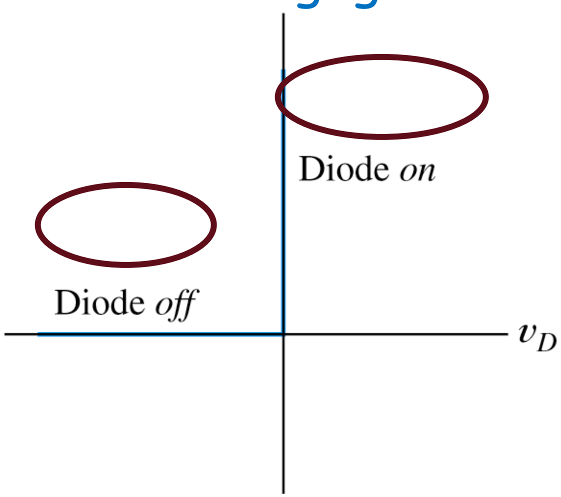
* Graphical load-line analysis is too cumbersome for complex circuits,

•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 on a diode and reverse currents are negligible.



Ideal-diode volt–ampere characteristic.

Ideal-Diode Model

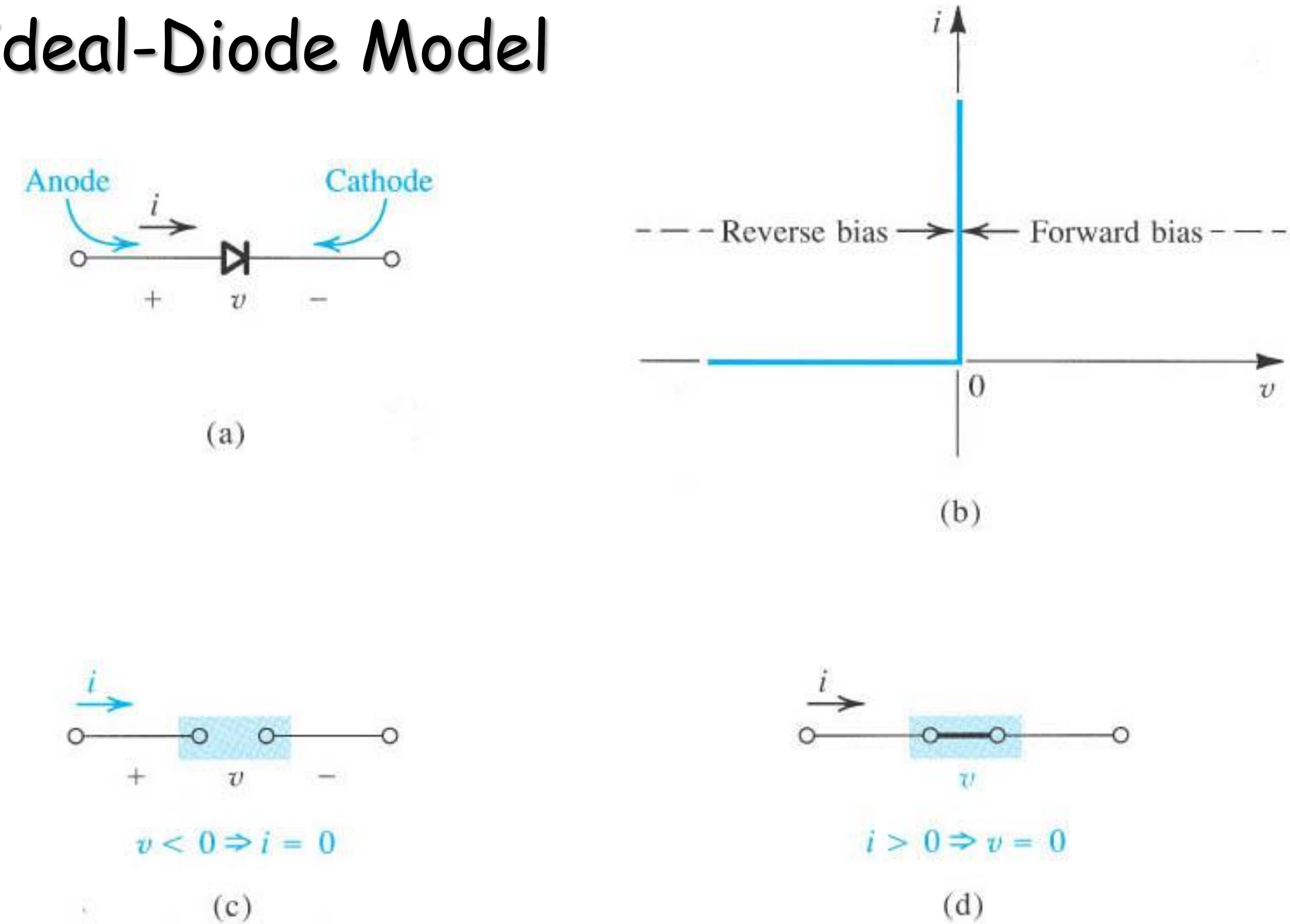
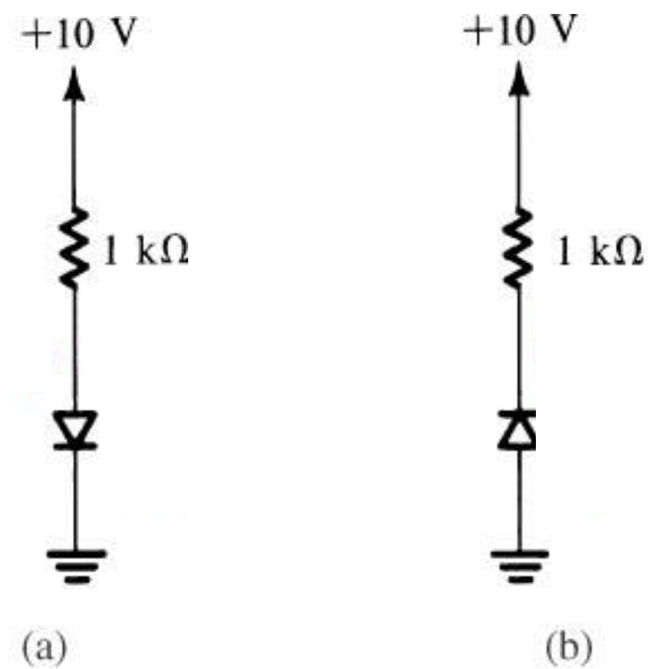


Figure The ideal diode: **(a)** diode circuit symbol; **(b)** *i*–*v* characteristic; **(c)** equivalent circuit in the reverse direction; **(d)** equivalent circuit in the forward direction.

Question: Calculate the voltage and current values of diodes by using ideal diode model.



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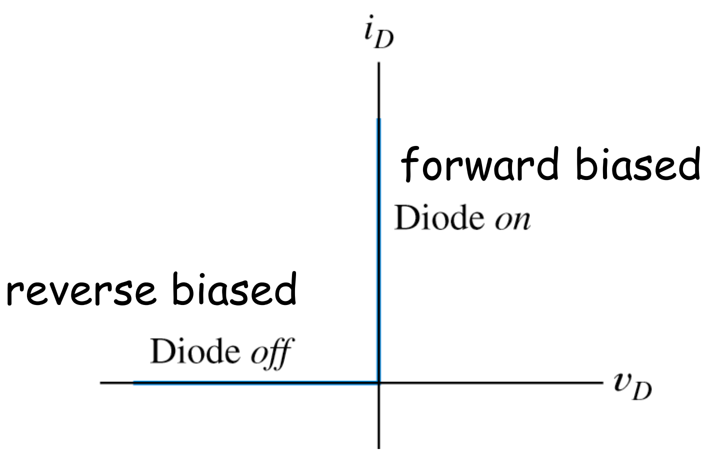
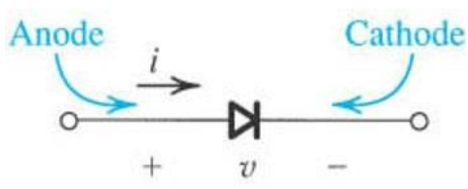
Ideal-Diode Model Analysis Method

* 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:

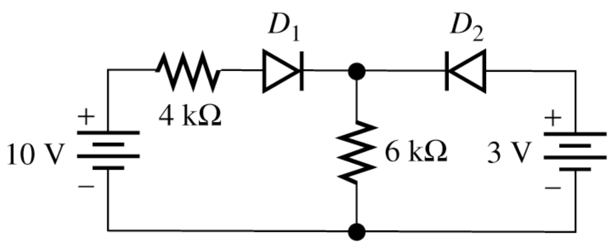
$$
\begin{aligned}
&(1)\ \text{For "assumed on diodes": check if } i_D \text{ is positive;}\\
&(2)\ \text{For "assumed off diodes": check if } v_D \text{ is negative}\\
&\Rightarrow \text{ALL YES} \Rightarrow \text{BINGO!}\\
&\Rightarrow \text{not ALL YES} \Rightarrow \text{make another guess....}\\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





Example – Analysis by Assumed Diode States

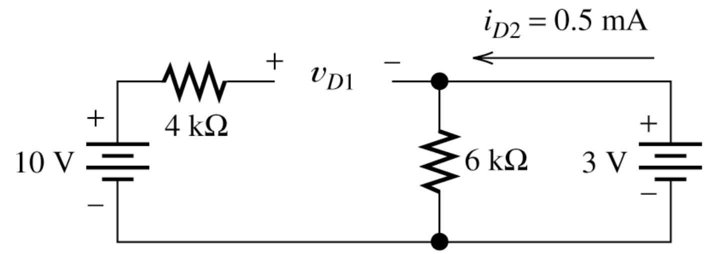
$\boxed{\textit{Analysis the circuit by assuming } D_1 \textit{ is off and } D_2 \textit{ on}}$



(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)

$\Downarrow$

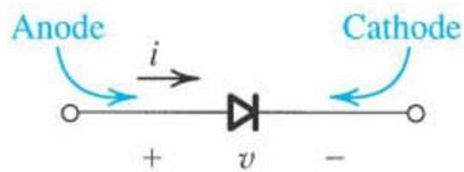
$$i_{D2} = 0.5mA \quad OK!$$

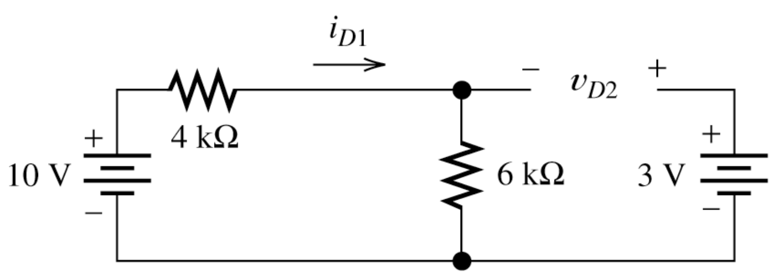
$$v_{D1} = 7V \quad not\ OK!$$

$\Downarrow$

(2) *assume*

D_1 *on*, D_2 *off*

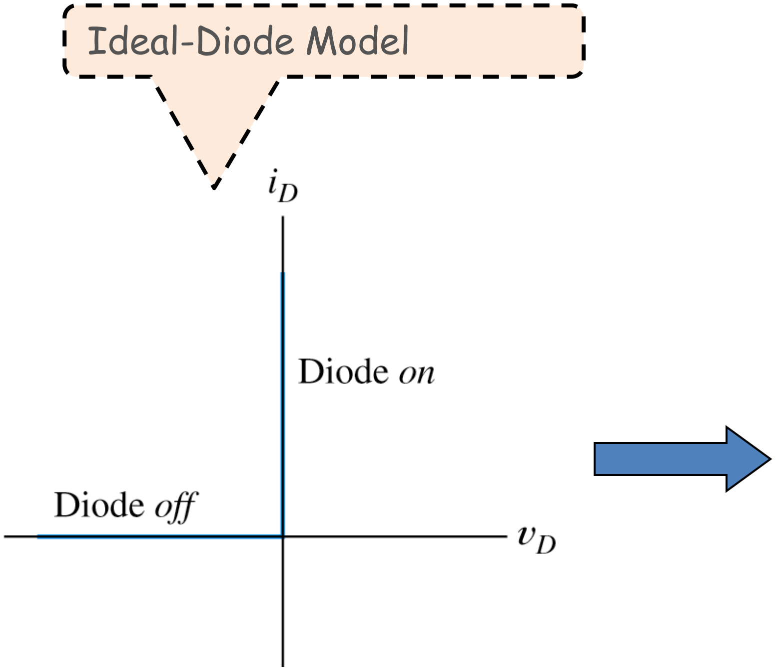


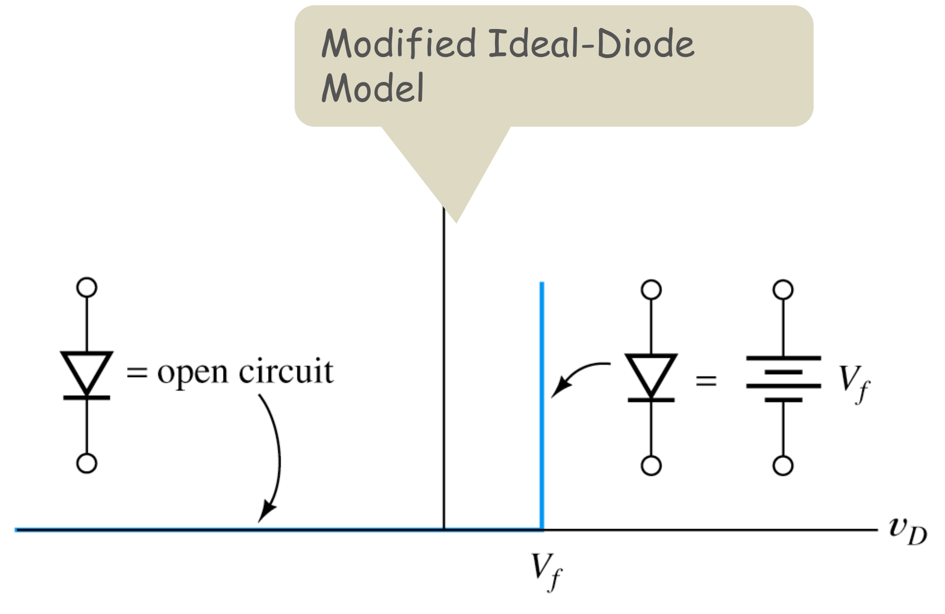


(c) Equivalent circuit assuming D_1 on and D_2 off (this is the correct assumption since i_{D1} turns out to be a positive value and v_{D2} turns out negative)

$$\boxed{\begin{aligned} \Rightarrow\ i_{D1} &= 1\,mA \quad OK! \\ v_{D2} &= \text{-}3\,V \quad OK! \end{aligned}}$$

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 Model

More accurate than the ideal diode model.

$\Delta V = R_a \Delta I$

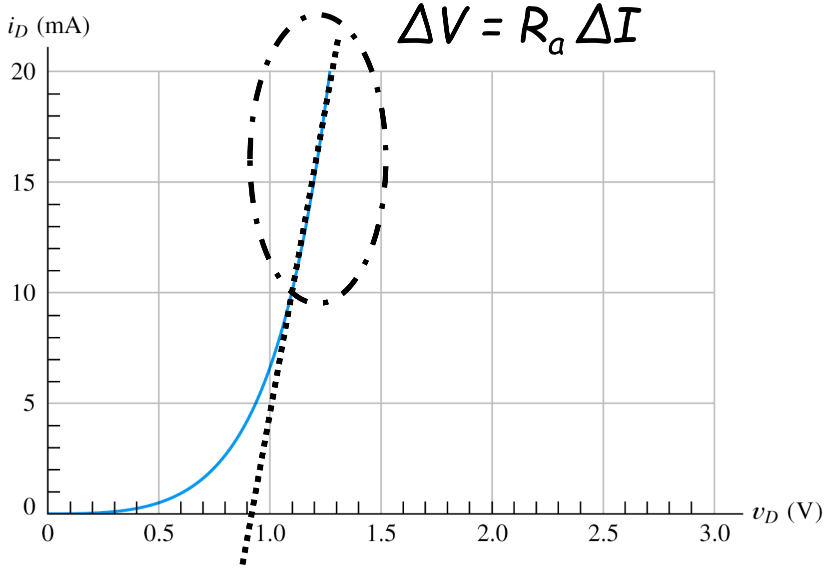
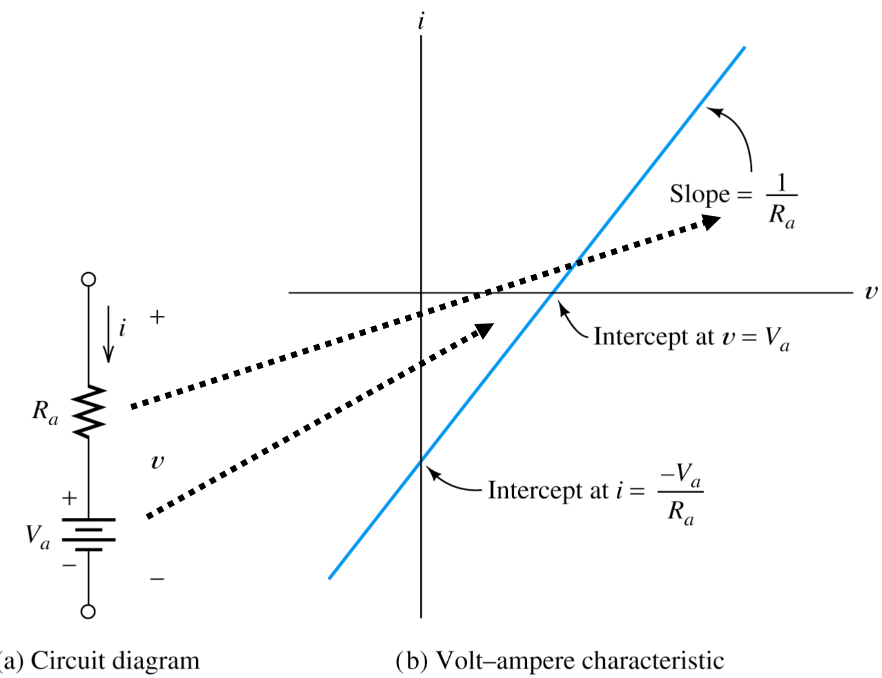


Figure 10.8 Diode characteristic for Exercise 10.3.

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

(2) We can model each section of the diode I-V curve with resistor (R_a) in series with a fixed voltage source (V_a)

$$\boxed{V = R_a i + V_a}$$



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

Example: Find circuit models for the **Zener-diode** volt-ampere curve shown in figure below using the piecewise-linear diode model.

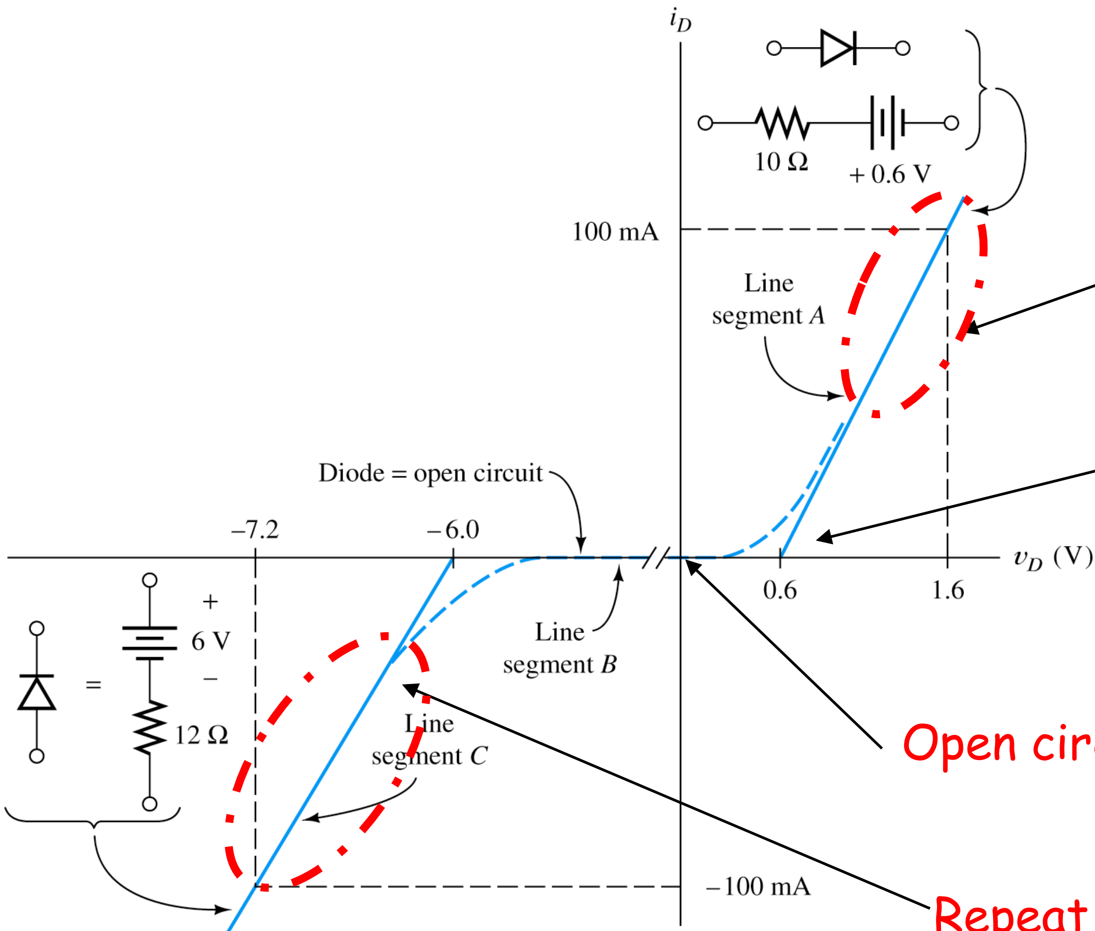


Figure 10.19 Piecewise-linear models for the diode of Example 10.6.

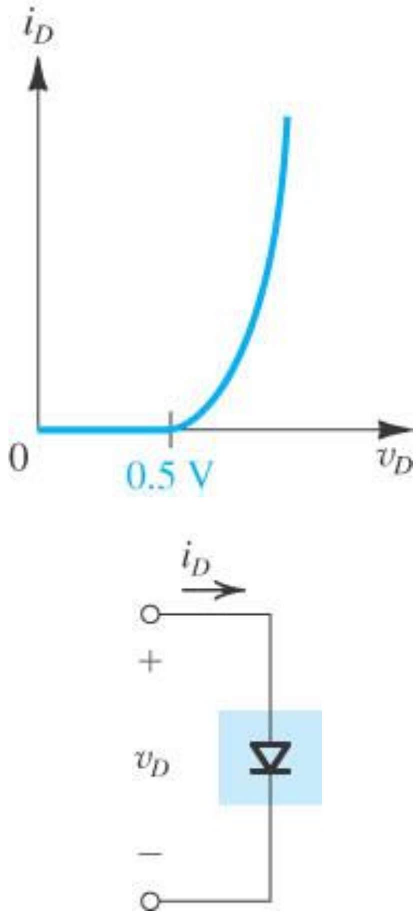
Draw a line

Look for intercept (0.6V) & the reciprocal of the slope (1/R) (1.6V-0.6V)/100mA=10Ω

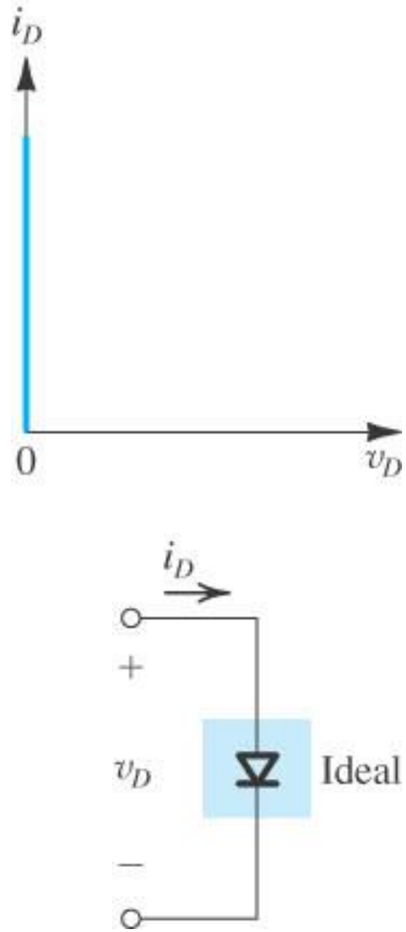
Open circuit approximation

Repeat for the reverse bias

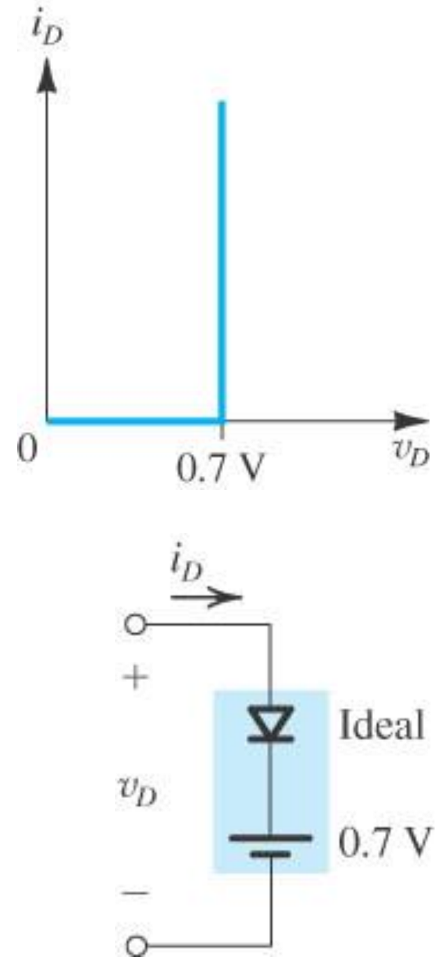
Diode curve



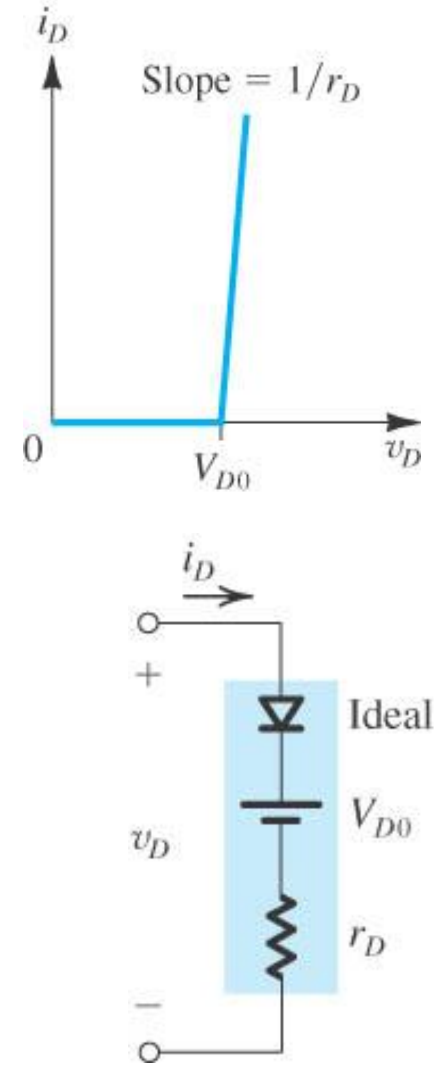
İdeal diode model



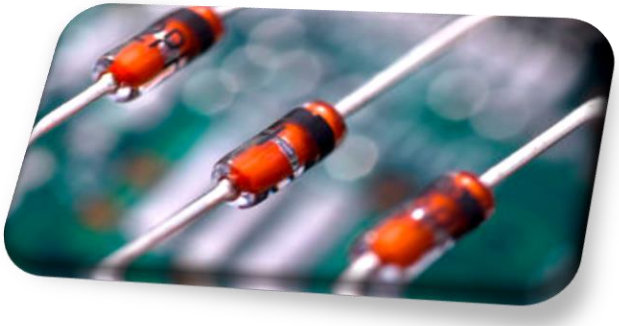
Modified ideal diode model

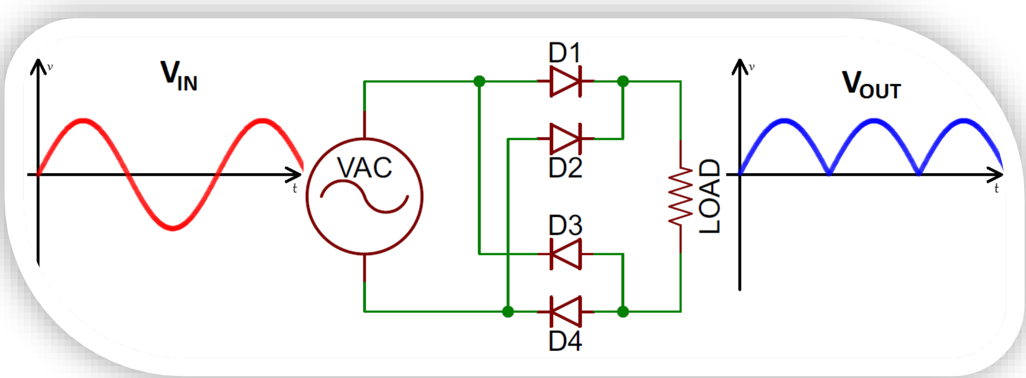


Piecewice linear diode model



Diode Applications



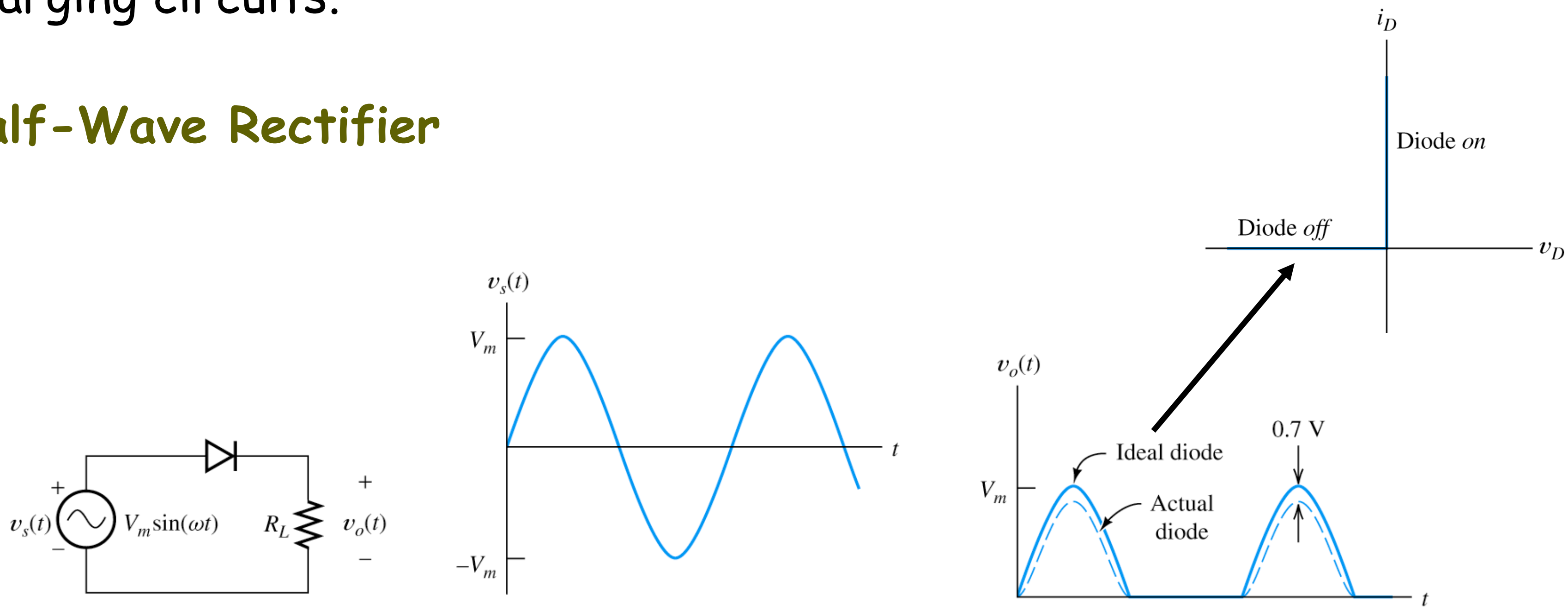


Rectifier Circuits

* *Rectifiers* convert AC power to DC power.

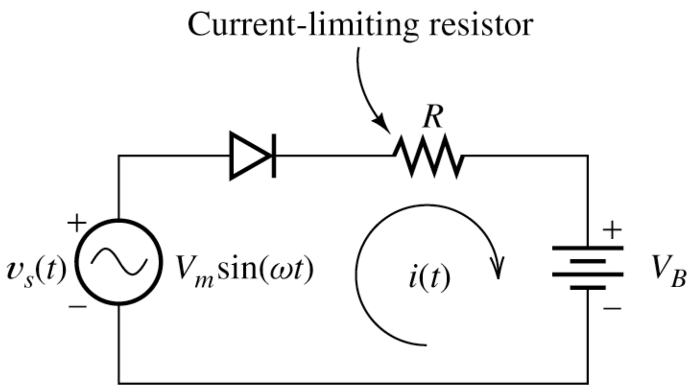
* Rectifiers form the basis for electronic power suppliers and battery charging circuits.

Half-Wave Rectifier

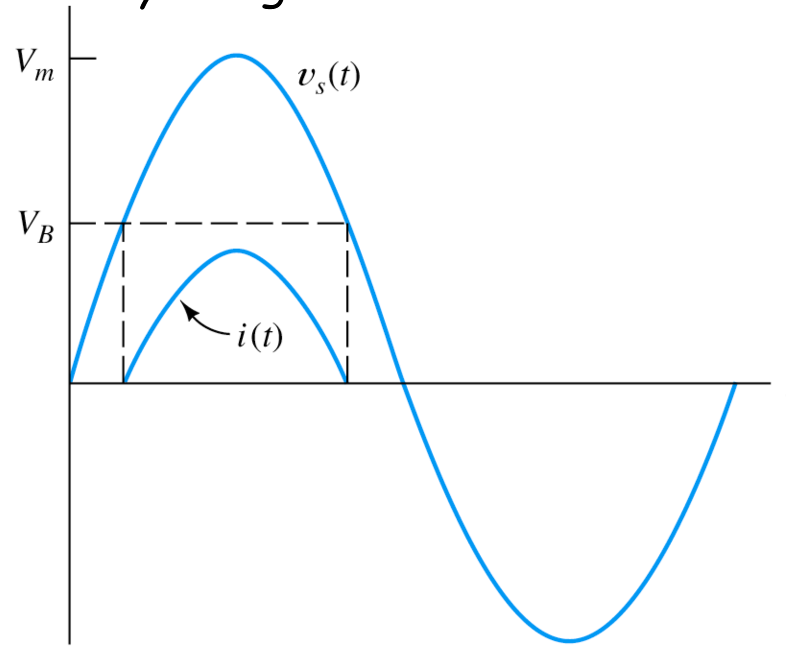


(a) Circuit diagram (b) Source voltage versus time (c) Load voltage versus time

Basic Battery-Charging Circuit



By using Ideal-Diode Model

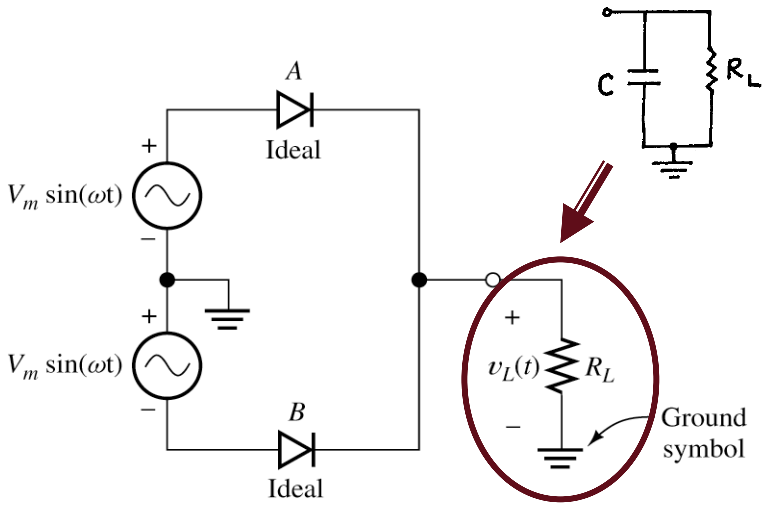


Half-wave rectifier used to charge a battery.

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

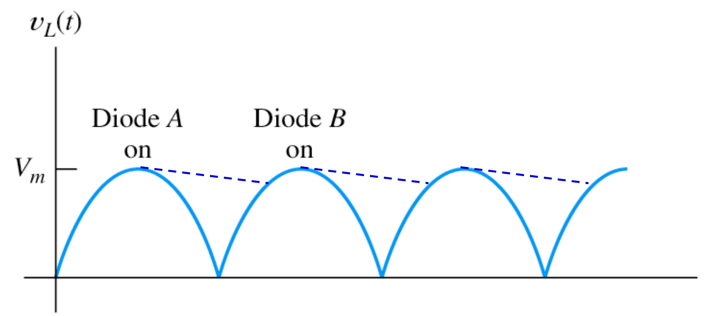
Full-Wave Rectifier Circuits

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



(a) Circuit diagram

By using Ideal-Diode Model



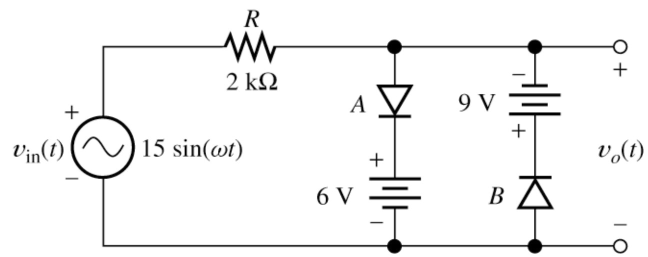
(b)

Two half-wave rectifier with a common ground.

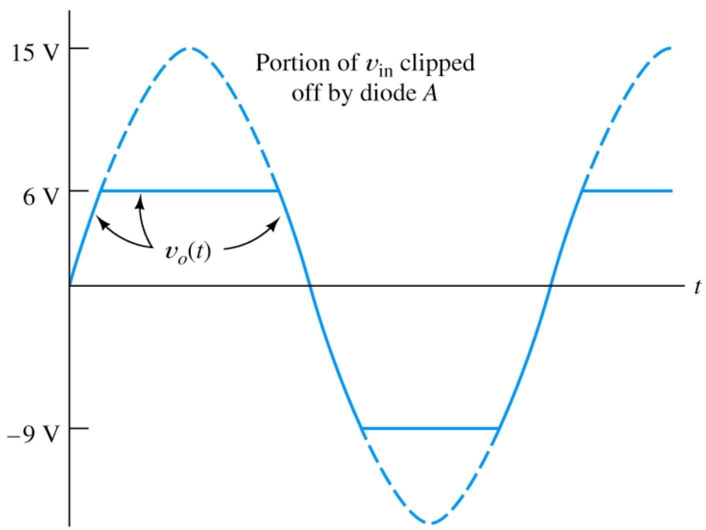
When **upper source** supplies "+" voltage to diode A, **the lower source** supplies "-" voltage to diode B; and vice versa.

Clipper Circuits <u>*By using Ideal-Diode Model*</u>

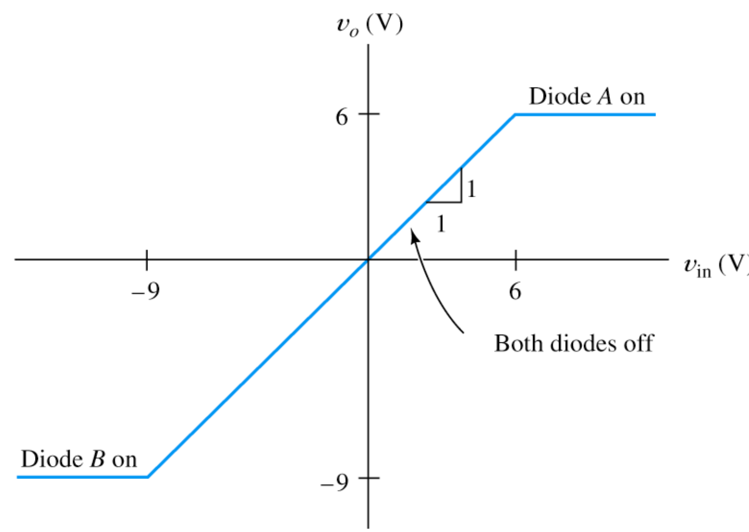
* A portion of an input signal waveform is "*clipped*" off.



(a) Circuit diagram

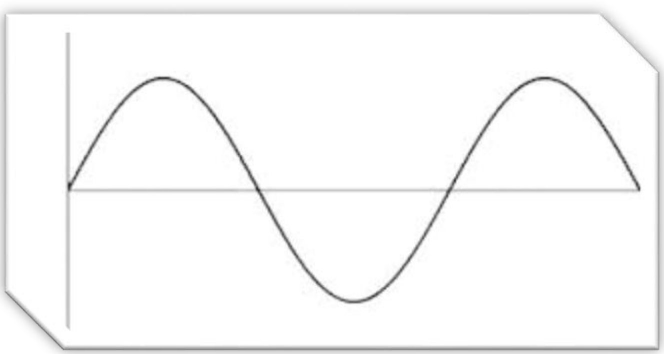


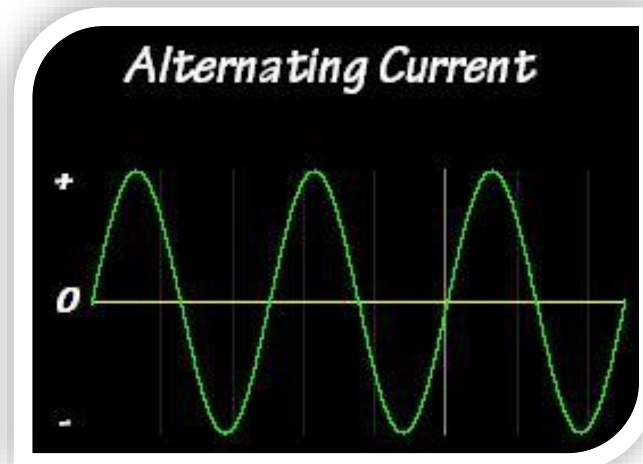
(b) Waveforms



(c) Transfer characteristic

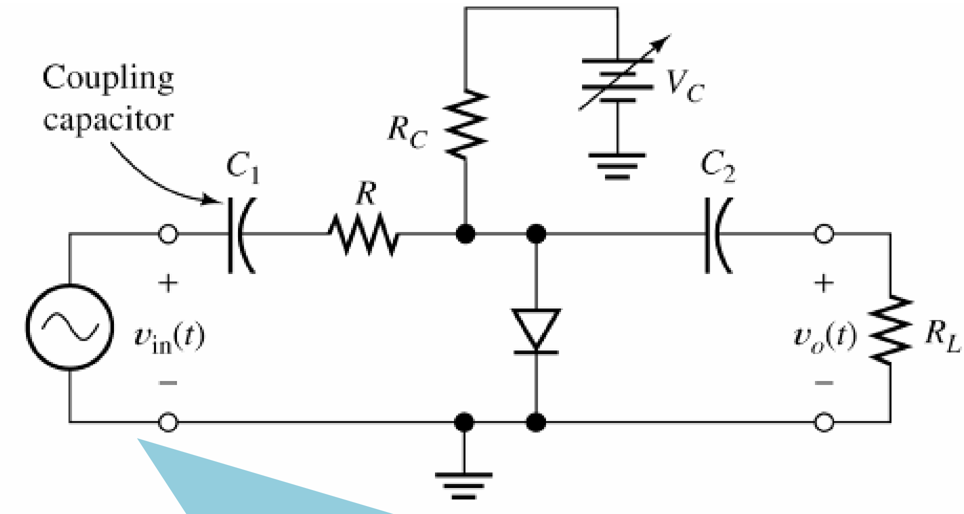
Small Signal Analysis of Diode

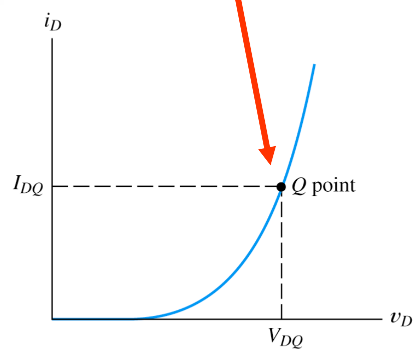




Linear Small-Signal Equivalent Circuits

- 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.





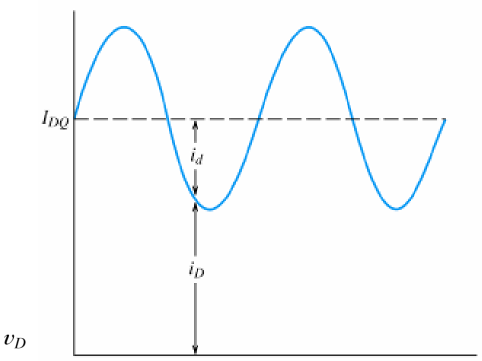


Illustration of diode currents.

Small-Signal is applied by a voltage source

* We often split the analysis of such circuit into two parts:

(1) Analyze the DC circuit to find operating point,

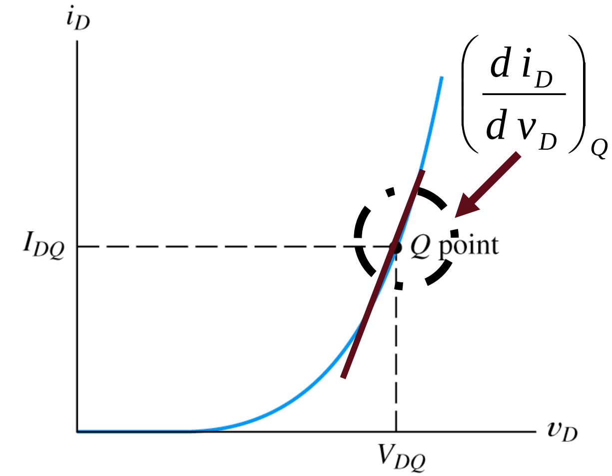
(2) Analyze the small signal (by using the "*linear small-signal equivalent circuit*".)

Linear Small-Signal Equivalent Circuits

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

THEN

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



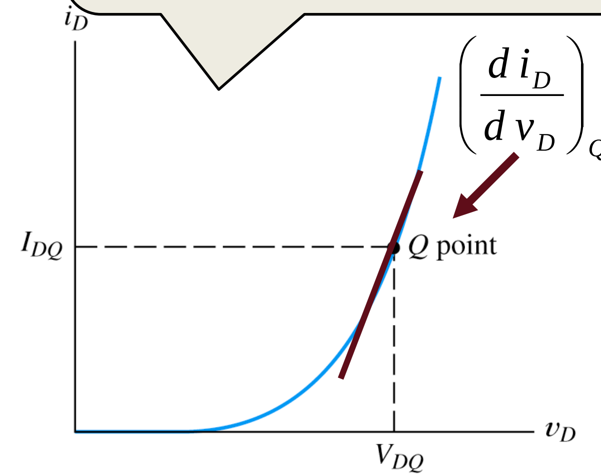
The small signal diode can be substituted by a single equivalent resistor.

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 input 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*

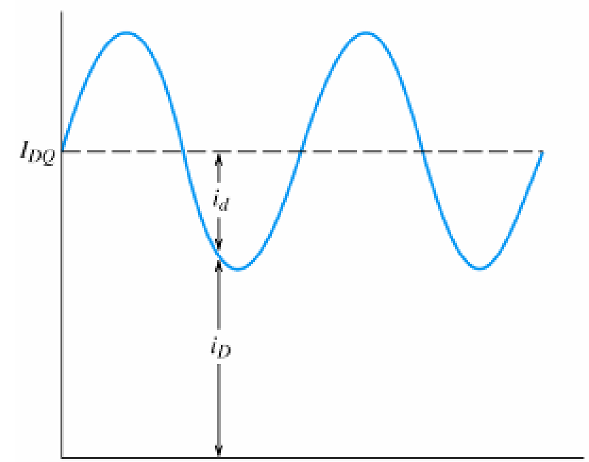


Illustration of diode currents.

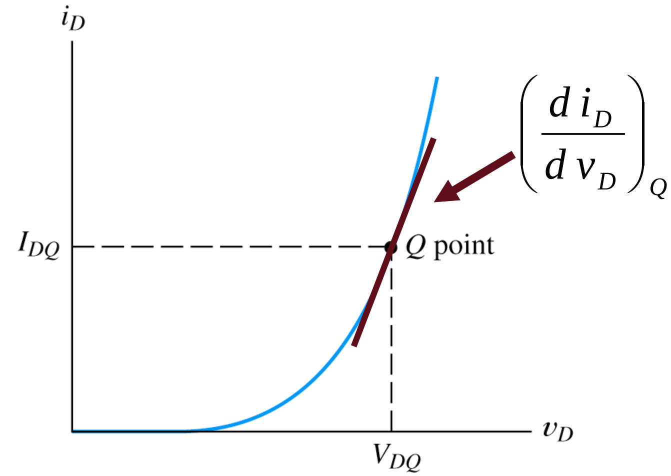
Linear Small-Signal Equivalent Circuits

$$r_d \cong \left[\left(\frac{d\, i_D}{d\, v_D} \right)_Q \right]^{-1}$$

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

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

By using these two equations, we can analyse *diode behavior* in small AC signal analysis.



Diode characteristic, illustrating the Q point

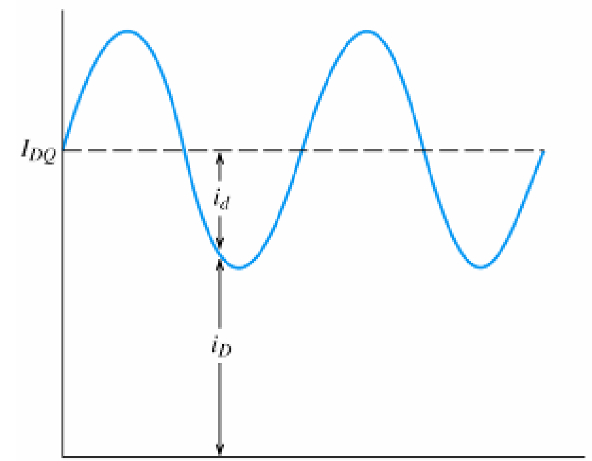
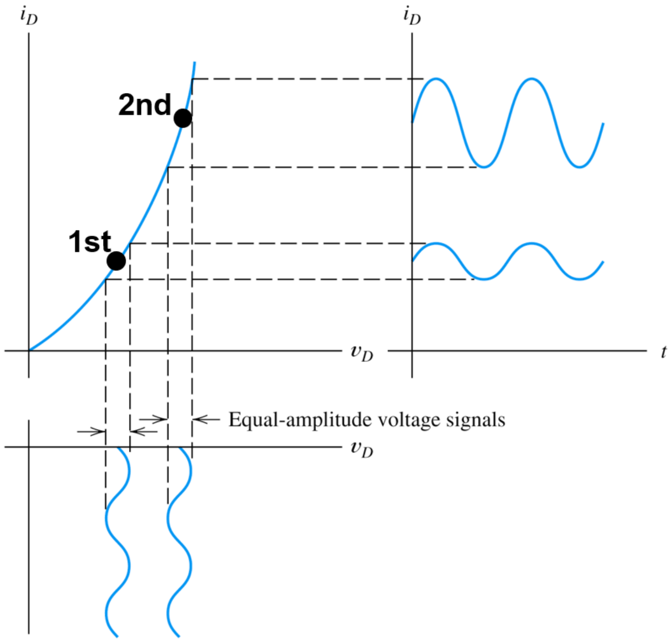


Illustration of diode currents.

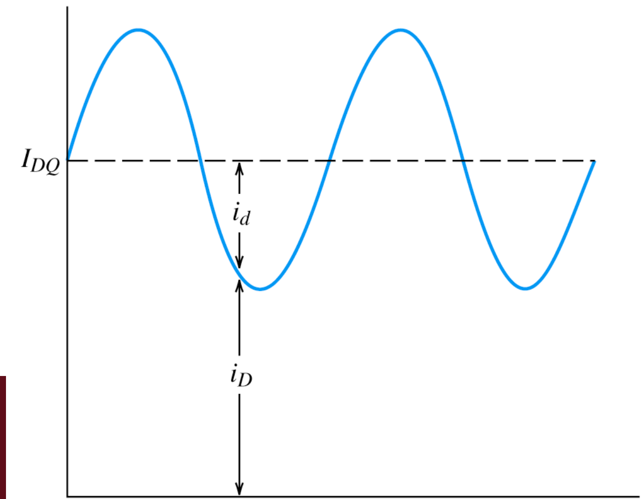
Linear Small-Signal Equivalent Circuits



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

$$i_D = I_{DQ} + i_d$$
$$v_D = V_{DQ} + v_d$$

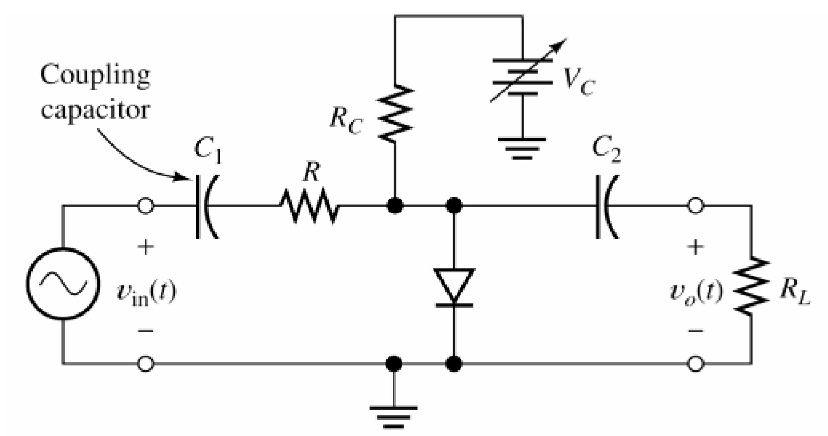
$$\boxed{i_d = \frac{v_d}{r_d}, \quad r_d = \frac{nV_T}{I_{DQ}}}$$



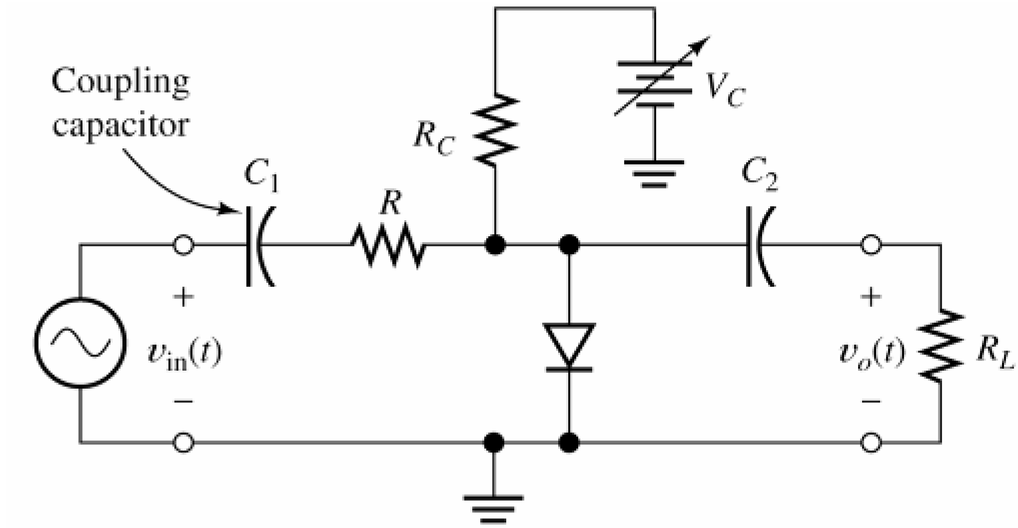
(1) V_{DQ} ***and*** I_{DQ} ***represent the dc signals at the Q point.***

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

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



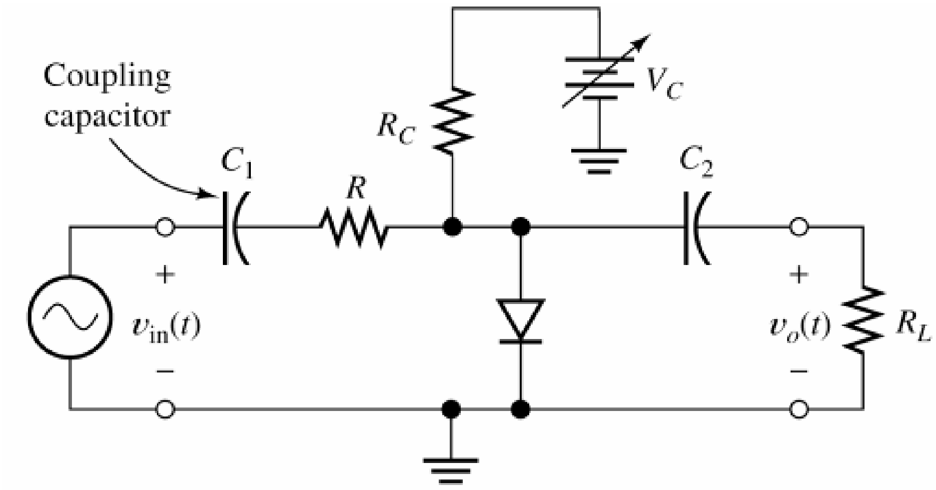
Voltage-Controlled Attenuator

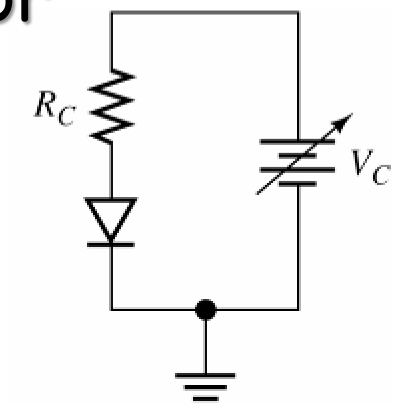


The function of this circuit is to produce an output signal that is a variable fraction of the AC input signal.

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.

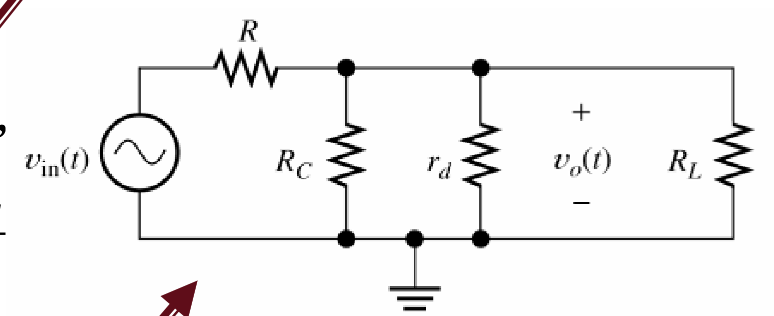
Voltage-Controlled Attenuator





First apply dc analysis to find the diode Q point,

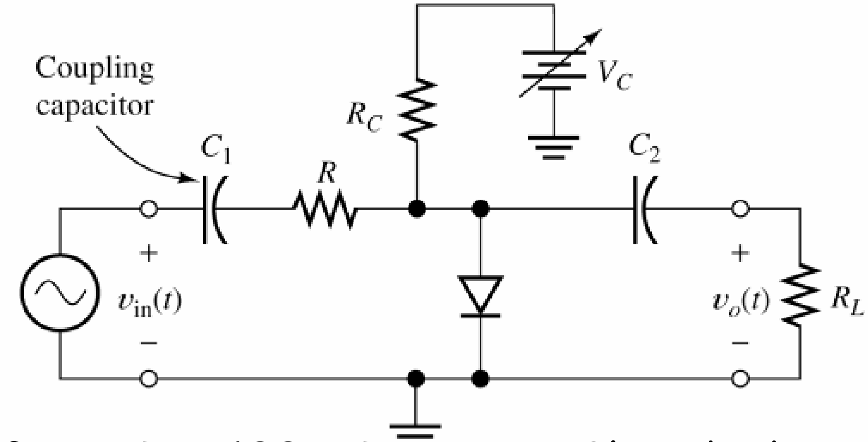
determine I_{DQ}*, then the* r_d *of the diode :* $r_d = \dfrac{nV_T}{I_{DQ}}$



Next, we perform small ac signal analysis :
DC voltage and current sources are removed.
The DC voltage source is equivalent to a short circuit for ac signal.

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

Exercise - Voltage-Controlled Attenuator



Evaluating we have

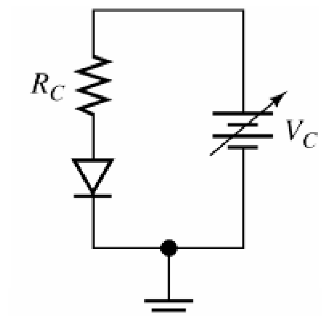
V_C (V)	1.6	10.6
I_{DQ} (mA)	0.5	5.0
r_d (Ω)	52	5.2
R_p (Ω)	49.43	5.173
A_v	0.3308	0.04919

Given: R = 100Ω, R_C = R_L = 2kΩ, diode n = 1 at 300K

Find the Q–point and A_v values for V_C = 1.6 and 10.6V (assuming $V_D = 0.6$V)

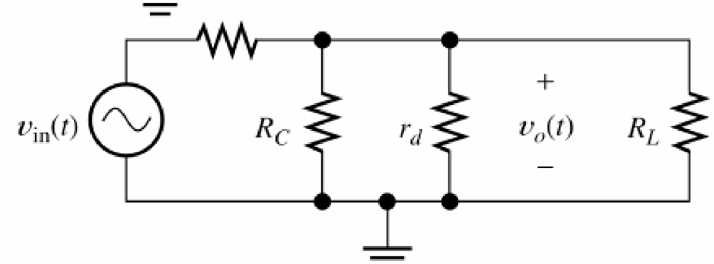
First apply DC analysis to find the diode Q point,

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

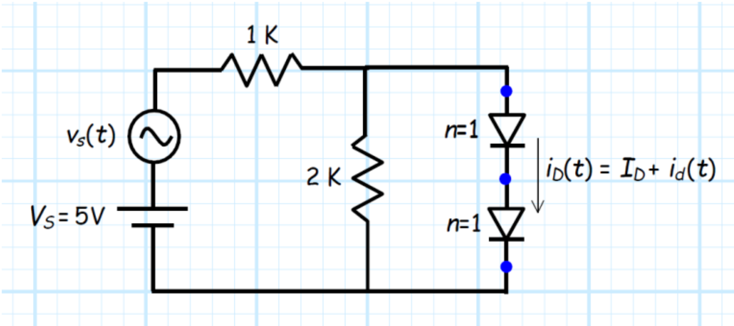


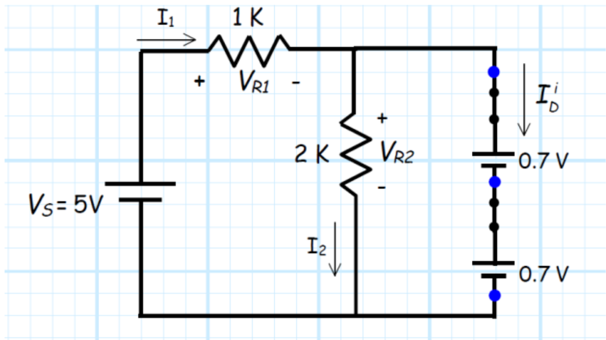
Next, we perform small AC signal analysis :

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



Question: *If $v_s(t)$= 0.01 sinωt, calculate $i_d(t)$* by using <u>Modified Ideal Diode Model</u> (V_d=0.7V) (n=1, V_T=25mV)





Step 1: D.C. Analysis

Small signal sources are removed.

KVL : $V_{R2} = 0.7 + 0.7 = 1.4\,V$

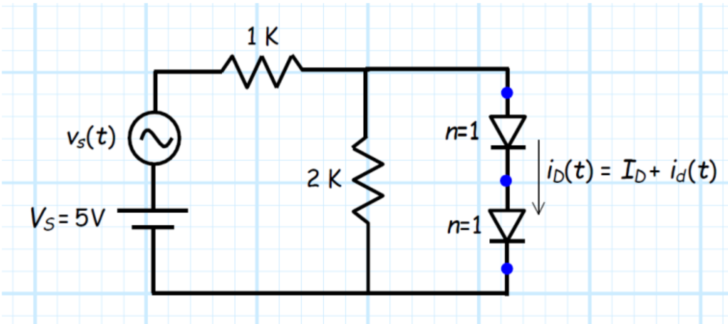
$$I_2 = \frac{V_{R2}}{2} = 0.7mA$$

$$V_{R1} = 5.0 - V_{R2} = 5.0 - 1.4 = 3.6\,V$$

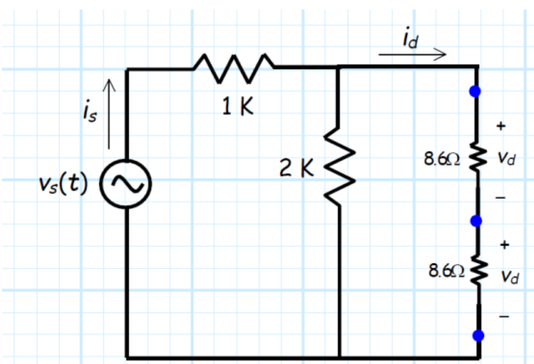
$$I_1 = \frac{V_{R1}}{1} = 3.6\,mA$$

$$I_D{}^i = I_1 - I_2 = 2.9mA$$

Question: *If $v_s(t)$= 0.01 sinωt, calculate $i_d(t)$* by using <u>Modified Ideal Diode Model</u> (V_d=0.7V)



$$r_D = \frac{nV_T}{I_D} = \frac{0.025}{0.0029} = 8.6\Omega$$



Step 2: A.C. Analysis

DC sources are removed. AC model of diode is placed.