ELE230 Electronics I

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Course Contents

- Semiconductor Diodes and Diode Applications
- DC and AC Analysis of Bipolar Junction Transistors (BJTs)
- DC and AC Analysis of Field Effect Transistors (FETs)
- Small-Signal Analysis of BJT and FET Amplifiers
- Frequency Response of BJT and FET Amplifiers
- Multistage Amplifiers

Textbook

Textbooks:

1. Boylestad and Nashelsky, ***Electronic Devices and Circuit Theory***, Prentice Hall, 8th ed.
2. Sedra and Smith, ***Microelectronic Circuits***, Oxford Press, 2009 (6th ed.)

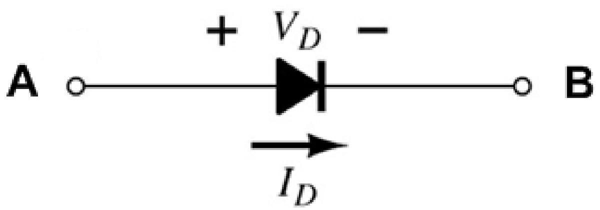
Supplementary books:

1. Millman and Halkias, ***Integrated Electronics***, McGraw-Hill.
2. Horowitz and Hill, ***The Art of Electronics***, Cambridge, 3rd ed.

Contents

Circuit Symbol

Diode is a nonlinear two-terminal device whose circuit symbol is like an arrowhead shown below.

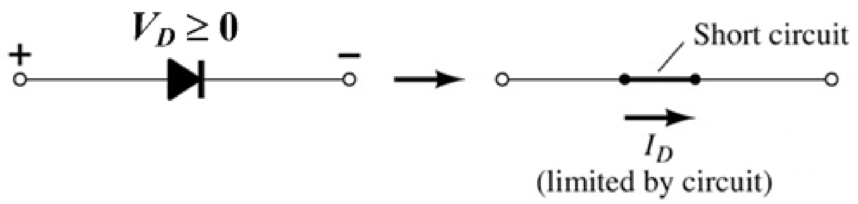


- Voltage across the diode, V_D, is normally defined as the voltage difference between back end of the arrowhead and front end of the arrowhead (voltage difference between terminal A and terminal B), i.e., $\boxed{V_D = V_A - V_B}$.
- Current through the diode, I_D, is defined in the direction of the arrowhead (flowing from terminal A to terminal B), i.e., $\boxed{I_D = I_{AB}}$.
- Diode is called **forward biased** (FB) when $V_A \geq V_B$, i.e., $V_D \geq 0$, and called **reverse biased** (RB) when $V_A < V_B$, i.e., $V_D < 0$.

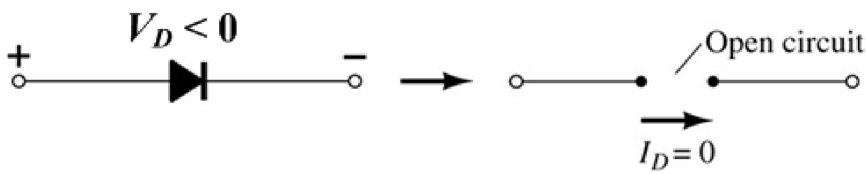
Ideal Diode Model

Ideally diode conducts current in only one direction and blocks current in the opposite direction. Thus,

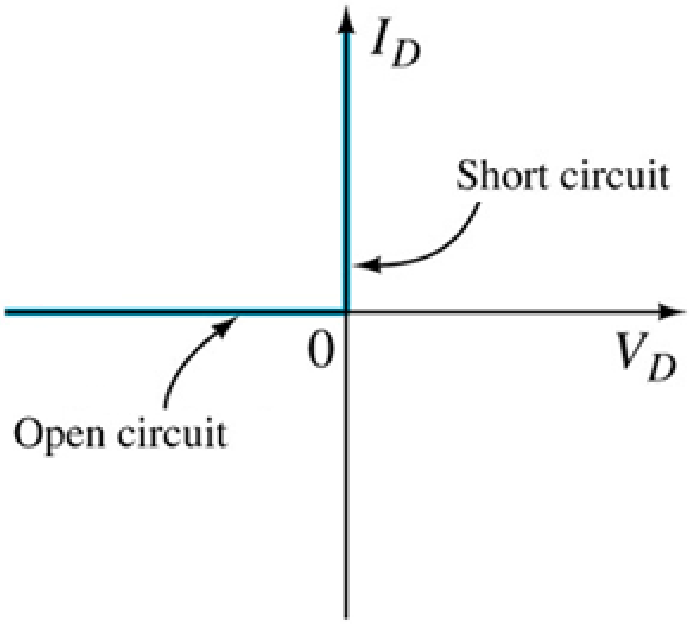
- Ideal diode is **short circuit** (i.e., ON) when it is **forward biased**.



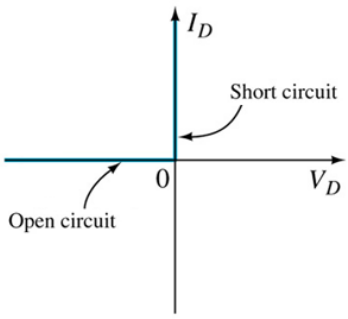
and **open circuit** (i.e., OFF) when it is **reverse biased**.



Consequently, characteristics curve of the ideal diode is given by



Ideal Diode Summary



$$\text{Ideal diode state} = \begin{cases} ON, & \text{if } V_D \geq 0 \\ OFF, & \text{if } V_D < 0 \end{cases}$$

Ideal Diode Model		
State	**Circuit Behaviour**	**Test Condition**
ON	$V_D = 0$	$I_D \geq 0$
OFF	$I_D = 0$	$V_D < 0$

If you make a **wrong assumption** about the state of the diode, then you will find that the **test condition will fail** (once you calculate the circuit voltage and currents).

- For example, if you have assumed the diode to be ON while it should be OFF, then you will find $I_D < 0$, failing the test condition.
- Similarly, if you have assumed the diode to be OFF while it should be ON, then you will find $V_D \geq 0$, failing the test condition.

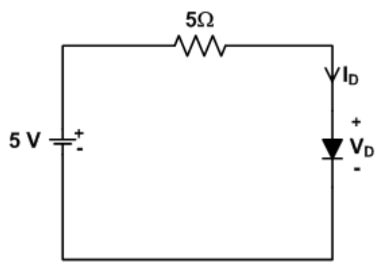
Using circuit behaviour and the test condition for the OFF state, let us devise a method to determine the state of the ideal diode.

Determining State of an Ideal Diode

1. Obtain the expression for V_D in terms of the diode current I_D from the electronic circuit.
2. Insert $I_D = 0$ in to this expression
3. Then, the diode state is given by

$$\text{Ideal diode state} = \begin{cases} ON, & \text{if } V_D|_{I_D=0} \geq 0 \\ OFF, & \text{if } V_D|_{I_D=0} < 0 \end{cases}$$

Example 1: Consider the circuit below and find I_D and V_D. Assume the diode is **ideal**.



Solution: First we need to determine the state of the ideal diode (i.e., ON or OFF). So, let us write down the KVL equation and obtain V_D

$$V_D = 5 - 5\,I_D$$

From the equation above, $V_D|_{I_D=0} = 5 \geq 0$. So, the diode is ON. Thus,

$$V_D = 0\,\text{V} \qquad \text{...from circuit behaviour}$$

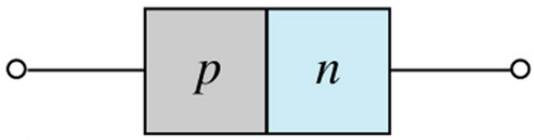
$$I_D = \frac{5 - V_D}{5} = \frac{5-0}{5} = 1\,\text{A}.$$

p-n Junction

In an **n-type** semiconductor, **majority carriers** are **electrons** and **minority carriers** are **holes**.

Similarly, in a **p-type** semiconductor, **majority carriers** are **holes** and **minority carriers** are **electrons**.

When we join n-type and p-type semiconductors (Silicon or Germanium) together, we obtain a p-n junction as shown below.



Current formed due to the movement of majority carriers across the junction is called the **majority carrier current**, I_{majority}.

Similarly, current formed due to the movement of minority carriers across the junction is called the **minority carrier current**, I_s. Note that, minority carrier and majority carrier currents flow in **opposite** directions.

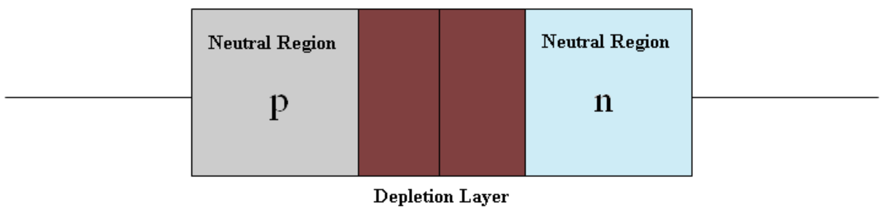
p-n Junction

When the materials are joined, the negatively charged atoms of the n-type side are attracted to the positively charged atoms of the p-type side.

Electrons in the n-type material migrate across the junction to the p-type material (electron flow).

Or, you could also say that holes in the p-type material migrate across the junction to the n-type material (conventional current flow).

The result is the formation of a **depletion layer** around the junction intersection, as shown below.



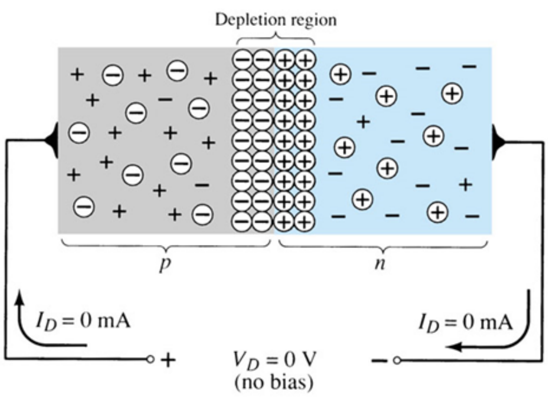
Normally, depletion layer is not symmetric around the intersection as the doping levels of n-side and p-side are usually not the same.

Operating Conditions

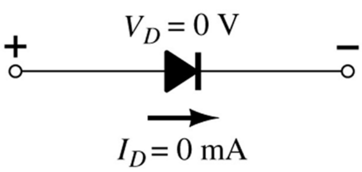
- **No Bias:** No voltage is applied and no current is flowing.
- **Reverse Bias:** Negative voltage (i.e., opposite polarity with the p-n junction) is applied.
- **Forward Bias:** Positive voltage (i.e., same polarity with the p-n junction) is applied.

No Bias Condition

- No external voltage is applied to the p-n junction as shown below. So, $V_D = 0\,\text{V}$ and no current is flowing $I_D = 0\,\text{A}$. Under no bias, only a modest depletion layer exists as seen in the figure below.

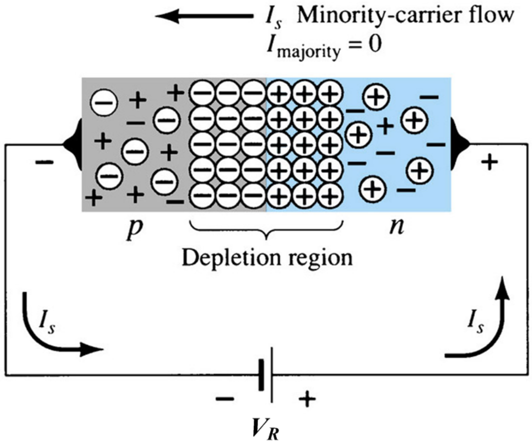


- No bias circuit behaviour is also shown below

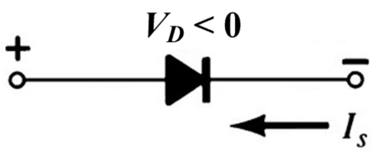


Reverse Bias Condition

- External voltage is applied across the p-n junction in the opposite polarity of the p- and n-type materials, as shown below.
- This causes the depletion layer to widen as shown below, as electrons in the n-type material are attracted towards the positive terminal and holes in the p-type material are attracted towards the negative terminal. Thus, the majority carrier current is zero, i.e., $I_{\text{majority}} = 0$.
- However, minority carriers move along the electric field across the junction forming the **minority carrier current**, I_s. Sometimes, this current is also called as the **reverse saturation current**.



- Reverse bias circuit behaviour is also shown below

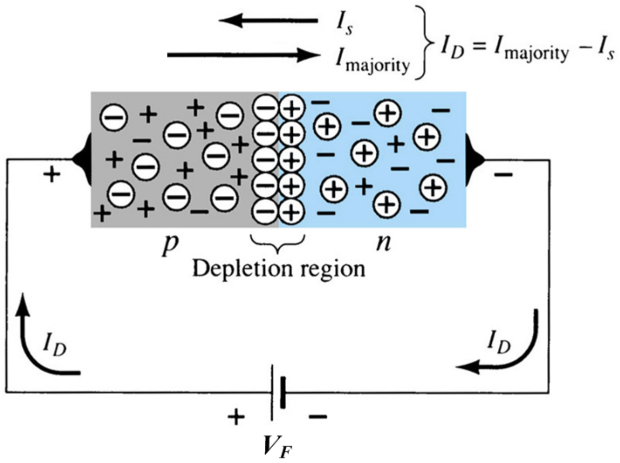


- Thus, diode current I_D under reverse bias is given by

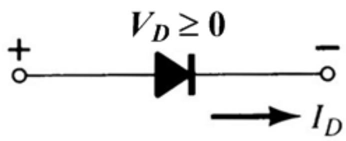
$$I_D = I_{\text{majority}} - I_s = 0 - I_s = -I_s.$$

Forward Bias Condition

- External voltage is applied across the p-n junction in the same polarity of the p- and n-type materials, as shown below.
- The depletion layer is narrow. So, electrons from the n-type material and holes from the p-type material have sufficient energy to cross the junction forming the **majority carrier current**, I_{majority}
- Minority carrier current I_s is still present in the opposite direction



- Forward bias circuit behaviour is also shown below



- Thus, diode current I_D under forward bias is given by

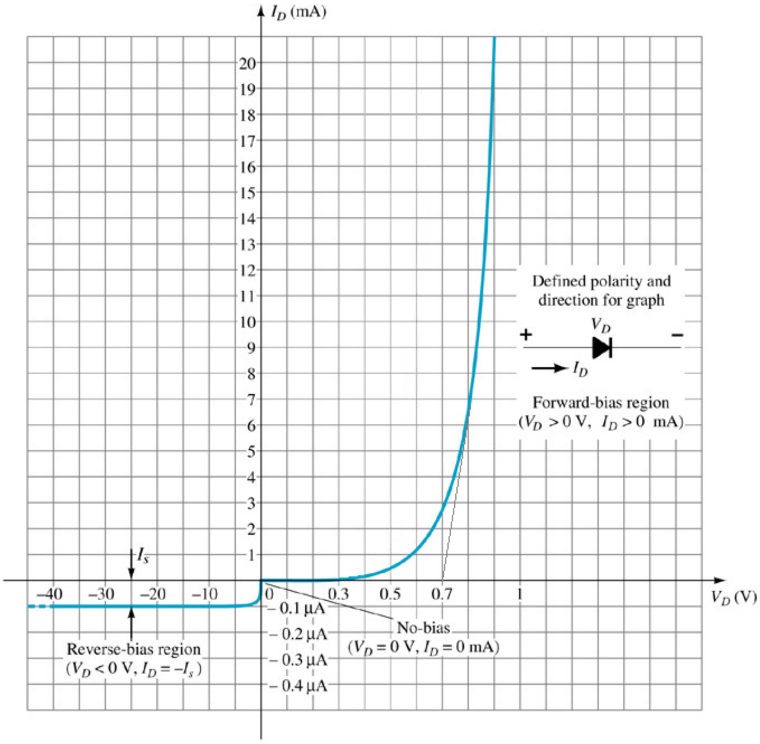
$$I_D = I_{\text{majority}} - I_s.$$

- Normally $I_{\text{majority}} \gg I_s$, so diode current I_D under forward bias is approximately equal to the majority carrier current, i.e.,

$$I_D \approx I_{majority}.$$

Diode Characteristic Equation

Empirically obtained diode **characteristics curve** covering all three operating conditions is shown below



- Diode characteristic equation (also known as the Shockley diode equation) describing the diode characteristics curve is given below

$$\boxed{I_D = I_s\left(e^{V_D/\gamma} - 1\right)}$$

where γ, sometimes expressed as V_T, is the **thermal voltage** given by

$$\gamma = \frac{kT}{q}$$

with k, q and T being the Boltzman constant, the charge of an electron and temperature in Kelvins, respectively. Note that, $\frac{k}{q}$ is constant given by

$$\frac{k}{q} = \eta\, 8.6173 \times 10^{-5}\,\text{V/K}$$

where $\eta = 1$ for Ge and $\eta = 2$ for Si for relatively low levels of diode current (at or below the knee of the curve) and $\eta = 1$ for Ge and Si for higher levels of diode current (in the rapidly increasing section of the curve). We can safely assume $\eta = 1$ for most cases.

- Under forward bias, diode characteristic equation simplifies (as $e^{V_D/\gamma} \gg 1$) to the **simplified forward bias diode equation** below

$$I_D \approx I_s e^{V_D/\gamma}$$

- Under reverse bias, diode characteristic equation simplifies (as $e^{V_D/\gamma} \ll 1$) to the following

$$I_D \approx -I_s$$

- Note that, γ only depends on the temperature (expressed in Kelvin units).

  So, thermal voltage γ at room temperature $T = 300\,\text{K}$ (i.e., $T = 27\,°\text{C}$) is given by

$$\boxed{\gamma = \gamma\,|_{T=300\,\text{K}} = 26\,\text{mV}.}$$

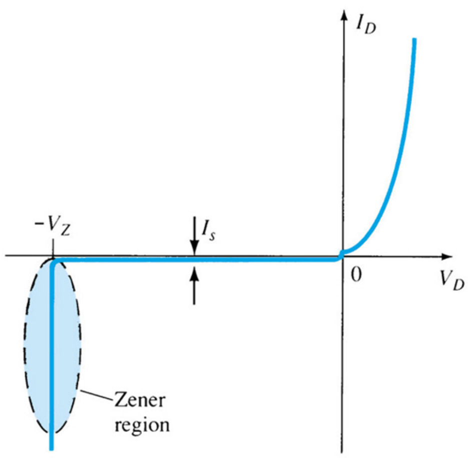
  If we take the room temperature as $T = 25\,°\text{C}$, then thermal voltage becomes

$$\gamma\,|_{T=298\,\text{K}} = 25\,\text{mV}.$$

  NOTE: Temperature in Kelvin (T) is obtained from the temperature in Celsius (T_C) as follows

$$T = T_C + 273$$

Zener Region (or Avalanche Breakdown Region)



As the voltage across the diode increases in the reverse-bias region, the velocity of the minority carriers responsible for the reverse saturation current I_s will also increase. Eventually, their velocity and associated kinetic energy will be sufficient to release additional carriers (i.e., avalanche effect) through collisions with otherwise stable atomic structures. That is, an ionization process will result whereby valence electrons absorb sufficient energy to leave the parent atom. These additional carriers can then aid the ionization process to the point where a high avalanche current is established and the **avalanche breakdown** region determined.

The avalanche region (V_Z) can be brought closer to the vertical axis by increasing the doping levels in the p- and n-type materials. However, as V_Z decreases to very low levels, such as $5\,\text{V}$, another mechanism, called **Zener breakdown**, will contribute to the sharp change in the characteristic.

It occurs because there is a strong electric field in the region of the junction that can disrupt the bonding forces within the atom and generate carriers generally **via tunnelling** (sometimes called as tunnelling breakdown) of the majority carriers under reverse-bias electric field when the valence band of the highly doped p-region is aligned with the conduction band of the highly doped n-region.

Although the Zener breakdown mechanism is a significant contributor only at lower levels of V_Z, this sharp change in the characteristic at any level is called the Zener region and diodes employing this unique portion of the characteristic of a p-n junction are called **Zener diodes**.

Peak Inverse Voltage (PIV) Rating

Avalanche breakdown region of the semiconductor diode must be avoided if the diode is supposed to work as an ON and OFF device.

The maximum reverse-bias potential that can be applied before entering the avalanche breakdown region is called the **peak inverse voltage** (referred to simply as the **PIV rating**) or the **peak reverse voltage** (denoted by **PRV rating**).

If an application requires a PIV rating greater than that of a single unit, a number of diodes of the same characteristics can be connected in series.

Similarly, diodes can be also connected in parallel to increase the current-carrying capacity.

Forward Bias Turn-On Voltage ($V_{D(ON)}$)

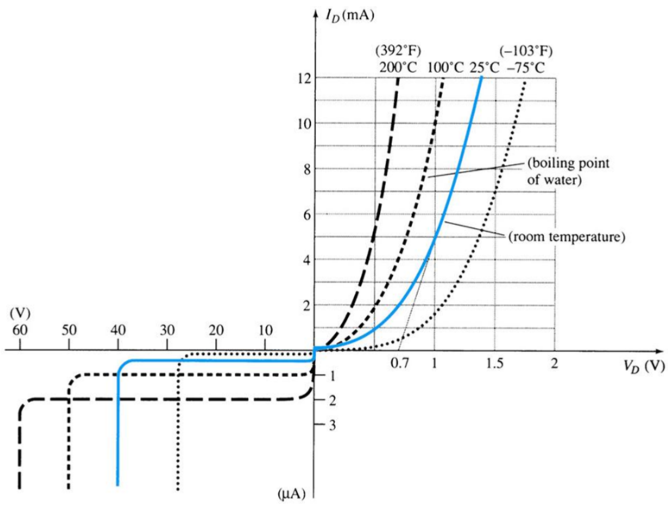
The point at which the diode changes from No Bias condition to Forward Bias condition happens when the electron and holes are given sufficient energy to cross the p-n junction. This energy comes from the external voltage applied across the diode.

This voltage (can be deduced from the diode characteristics curve) is called the **turn-on voltage** or the **threshold voltage**, and denoted by $V_{D(ON)}$ (V_T or V_0 notations are also used).

The forward bias voltage required to turn on the diode for a

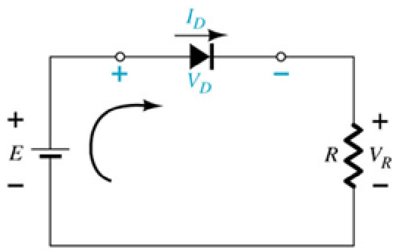
- Silicon diode: $V_{D(ON)} = 0.7\,\text{V}$
- Germanium diode: $V_{D(ON)} = 0.3\,\text{V}$

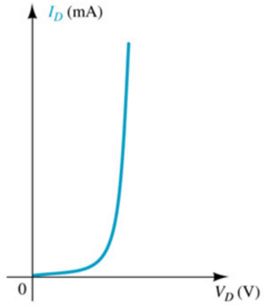
Temperature Effects



- As temperature increases it adds energy to the diode. From the figure above, as temperature increases
  - It **reduces** the required **turn-on voltage** ($V_{D(ON)}$) in forward bias condition,
  - It **increases** the amount of **reverse saturation current** (I_s) in reverse bias condition,
  - It **increases** the **avalanche breakdown voltage** in reverse bias condition.
- Germanium diodes are more sensitive to temperature variations than Silicon diodes.

Load Line and Operating Point (Q-point)





From the figure on the left above, we obtain

$$V_D = E - I_D R$$

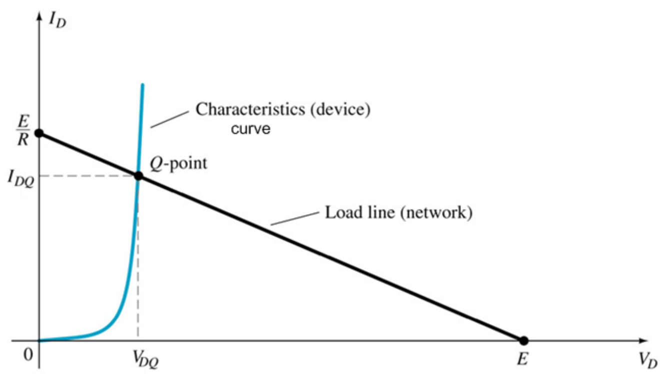
- We can rearrange the circuit equation above to get I_D on the left-hand side of the equation, i.e.,

$$\boxed{I_D = \frac{-1}{R} V_D + \frac{E}{R}}$$

- This equation obtained from the diode circuit is called the **load line equation**.

  The **load line** equation gives us all the possible current (I_D) values for all the possible voltage (V_D) values obtained across the diode in a given circuit.

- Once we draw the load line over the diode characteristics curve given in the figure on the right in the previous slide, and the intersection point will give us the solution (I_{DQ}, V_{DQ}) of the diode current and diode voltages I_D and V_D for the given circuit, respectively. The result is shown below.



- This plot is called the **load line plot**. Also, the intersection point of the load line and the diode characteristics curve is called the **operating point** or the **Q-point** specified by the (I_{DQ}, V_{DQ}) pair. Note that Q stands for quiescent (i.e., still).

- For some examples, see Examples 2.1, 2.2 and 2.3 in the Boylestad and Nashelsky textbook (8th ed.).

A load line plot like the figure in the previous slide is actually the graphical way of solving the diode characteristics equation

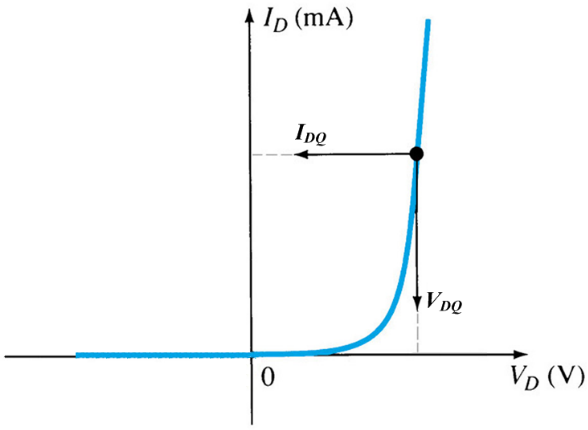
$$I_D = I_S \left(e^{V_D/\gamma} - 1 \right)$$

and the electrical circuit equation, i.e., load line equation

$$I_D = -\frac{V_D}{R} + \frac{E}{R}$$

simultaneously. Load line plots are very practical and more efficient than solving these two equations analytically.

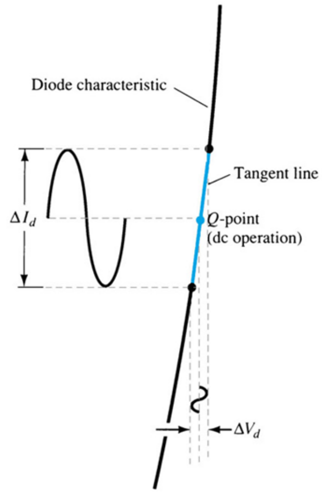
DC Resistance (Static Resistance)



- For a specific applied DC voltage V_{DQ}, the diode will have a specific current I_{DQ}, and consequently a specific resistance R_{DQ}. The amount of resistance R_{DQ}, depends on the applied DC voltage and current.
- For a given operating point as shown above, we can find the DC resistance as follows

$$R_{DQ} = \left. \frac{V_D}{I_D} \right|_{Q\text{-point}} = \frac{V_{DQ}}{I_{DQ}}$$

AC Resistance (Dynamic Resistance)



- Dynamic resistance r_d is determined around a Q-point as the ratio of given very small voltage variation ΔV_d to the current variation ΔI_d obtained, i.e., $r_d \cong \left.\frac{\Delta V_d}{\Delta I_d}\right|_{Q\text{-point}}$.
- As the magnitude of these small voltage and current variations go to zero this equation for the dynamic resistance r_d approaches to the following partial derivative

$$\boxed{r_d = \left.\frac{\partial V_D}{\partial I_D}\right|_{Q\text{-point}}}$$

- In the **forward bias region**, we can use the simplified forward bias diode equation

$$I_D \approx I_s e^{V_D/\gamma}$$

Then, the forward bias dynamic resistance is obtained as

$$r_d = \left.\frac{\partial V_D}{\partial I_D}\right|_{Q\text{-point}} = \left.\frac{1}{\frac{\partial I_D}{\partial V_D}}\right|_{Q\text{-point}} \approx \frac{1}{\frac{1}{\gamma}\underbrace{I_s\, e^{V_{DQ}/\gamma}}_{I_{DQ}}}$$

$$= \frac{\gamma}{I_{DQ}}$$

The forward bias dynamic resistance depends on the Q-point current I_{DQ} and the temperature, i.e.,

$$\boxed{r_d = \frac{\gamma}{I_{DQ}}}$$

We know that $\gamma = 26\,\text{mV}$ at room temperature ($300\,\text{K}$), so the diode dynamic resistance can be calculated as

$$r_d = \frac{26\,\text{mV}}{I_{DQ}}$$

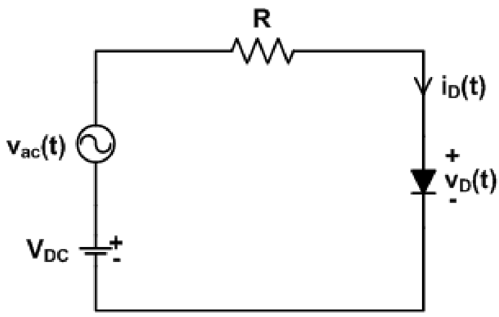
- In the **reverse bias region**, diode current is approximately constant

$$I_D \approx -I_s$$

So, the reverse bias dynamic resistance is essentially infinite, i.e.,

$$r_d = \infty.$$

DC and Small-Signal AC (SSAC) Analysis



- Here, it is given that $V_{DC} - \text{peak}(v_{ac}(t)) > V_{D(ON)}$ and $V_{DC} >> \text{peak}(v_{ac}(t))$.

  First condition ensures that the diode state do not change for any value of the AC signal (i.e., diode is always ON) and the second condition ensures that diode behaviour is approximately linear around the Q-point.

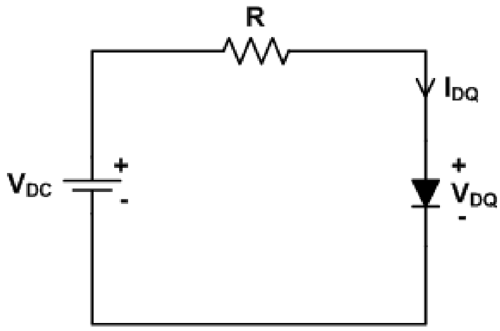
  The two conditions together provide **linearity** (approximately), so that we can employ the **superposition theorem**. Remember that, superposition theorem can only be employed in linear systems.

- Then, we can apply the **superposition theorem** and express the diode current and voltages as follows

$$i_D(t) = I_{DQ} + i_d(t)$$
$$v_D(t) = V_{DQ} + v_d(t).$$

- Diode is always ON and magnitude of the AC signal is very small compared to the DC signal (e.g., $10\,\text{mV}$ vs. $10\,\text{V}$). So, we can apply the **law of superposition** and perform DC analysis and small-signal AC (SSAC) analysis **separately**, that is, we obtain I_{DQ} and $i_d(t)$ independently using different circuits.

- We obtain **DC equivalent circuit** by killing the AC sources as shown below

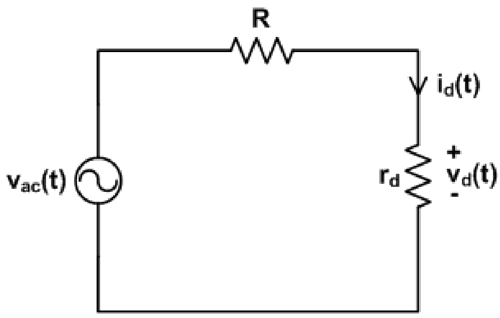


In DC analysis, I_{DQ} and V_{DQ} are found using the **load-line analysis**, i.e., by solving the diode characteristic equation and load-line equation simultaneously.

- We obtain **SSAC equivalent circuit** by killing the DC sources and replacing the diode with **its SSAC model (r_d)** where

$$r_d = \frac{26\,\text{mV}}{I_{DQ}}$$

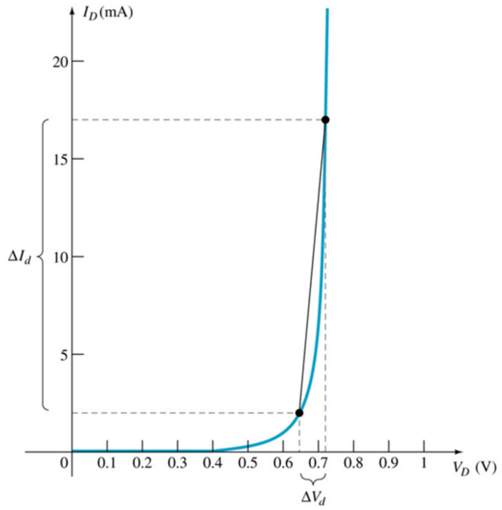
as shown below



- In SSAC analysis, diode is replaced by its dynamic resistance r_d and we can finally find $i_d(t)$ and $v_d(t)$ as follows

$$i_d(t) = \frac{v_{ac}(t)}{R + r_d}$$
$$v_d(t) = \frac{r_d}{R + r_d}\, v_{ac}(t).$$

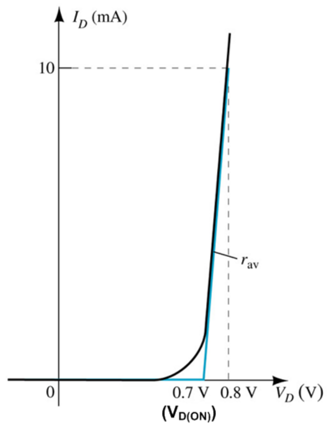
Average AC Resistance

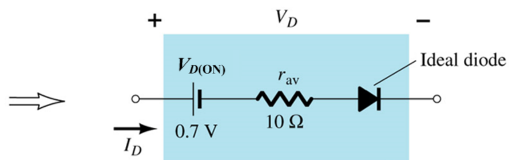


- Average AC resistance can be determined by picking two points on the characteristic curve developed for a particular circuit where the voltage and current variations (i.e., ΔV_d and ΔI_d) are large. It is used to develop the piecewise-linear diode model.
- Thus, the average AC resistance r_{av} is calculated as

$$r_{\text{av}} = \frac{\Delta V_D}{\Delta I_D} \quad \text{(point-to-point)}$$

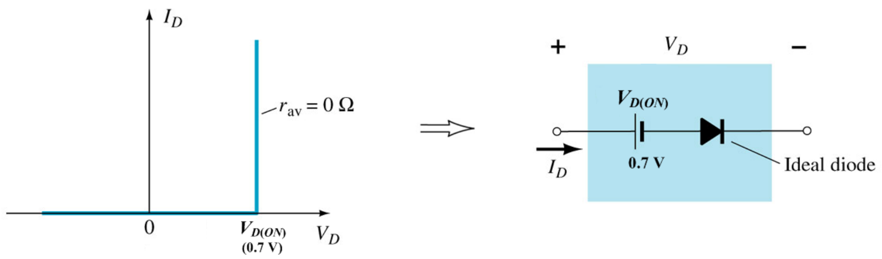
Piecewise-Linear Diode Model





- Piecewise-linear approximation of the diode characteristics curve is obtained and depicted as the blue lines on the left of the figure above.
- Similarly, obtained piecewise-linear equivalent circuit is shown on the right of the figure above.
- Here, r_{av} is the forward bias average AC resistance (i.e., **internal resistance**) of the diode.

Simplified Diode Model



- Simplified diode characteristics curve is obtained and shown on the left of the figure above.
- Similarly, obtained simplified equivalent circuit is shown on the right of the figure above.

$$\text{Diode state} = \begin{cases} ON, & \text{if } V_D \geq V_{D(ON)} \\ OFF, & \text{if } V_D < V_{D(ON)} \end{cases}$$

Simplified Diode Model		
State	**Circuit Behaviour**	**Test Condition**
ON	$V_D = V_{D(ON)}$	$I_D \geq 0$
OFF	$I_D = 0$	$V_D < V_{D(ON)}$

- For the ideal diode model, the turn-on voltage is zero, i.e., $V_{D(ON)} = 0\,$V.

In this course, we will mostly use the simplified diode model unless otherwise stated.

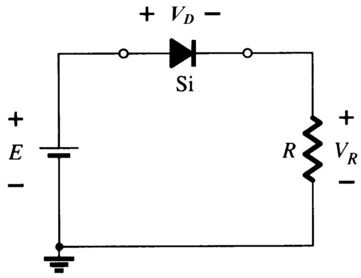
- Using circuit behaviour and the test condition for the OFF state, let us devise a method to determine the state of a diode under simplified diode model.

Determining State of a Diode

1. Obtain the expression for V_D in terms of the diode current I_D from the electronic circuit.
2. Insert $I_D = 0$ in to this expression
3. Then, the diode state is given by

$$\text{Ideal diode state} = \begin{cases} ON, & \text{if } V_D|_{I_D=0} \geq V_{D(ON)} \\ OFF, & \text{if } V_D|_{I_D=0} < V_{D(ON)} \end{cases}$$

Example 2: Consider the circuit below and find I_D and V_D with $V_{D(ON)} = 0.7\,\text{V}$ and $E > 0.7\,\text{V}$.



Solution: First we need to determine the state of the diode (i.e., ON or OFF). So, let us write down the KVL equation and obtain V_D

$$V_D = E - I_D\,R$$

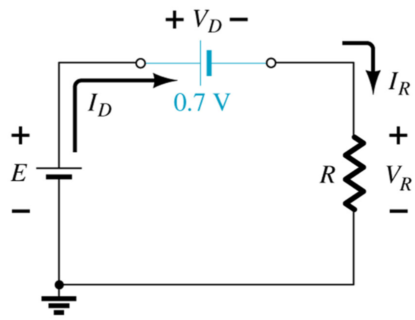
From the equation above, $V_D|_{I_D=0} = E \geq V_{D(ON)}$. So, the diode is ON. Thus,

$$V_D = V_{D(ON)} = 0.7\,\text{V} \qquad \text{...from circuit behaviour}$$

$$I_D = \frac{E - V_D}{R} = \frac{E - 0.7}{R}$$

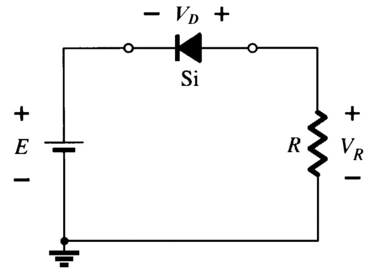
$$V_R = E - V_D = E - 0.7$$

Thus, our diode circuit is simplified to the circuit shown below



Note that $I_R = I_D$.

Example 3: Consider the circuit below and find I_D and V_D with $V_{D(ON)} = 0.7\,\text{V}$ and $E > 0.7\,\text{V}$.



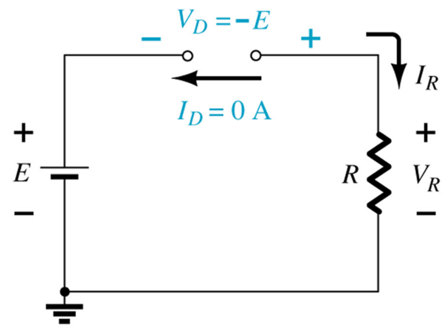
Solution: First we need to determine the state of the diode (i.e., ON or OFF). So, let us write down the KVL equation and obtain V_D

$$V_D = -E - I_D\,R$$

From the equation above, $V_D|_{I_D=0} = -E < V_{D(ON)}$. So, the diode is OFF. Thus,

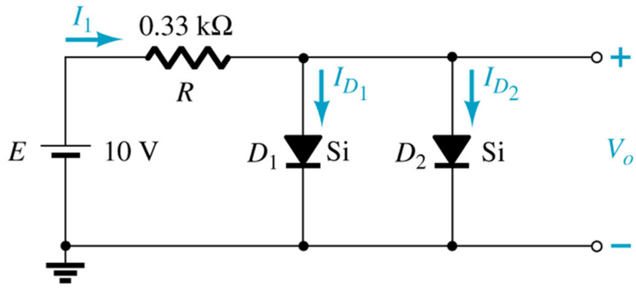
$$I_D = 0\,\text{A} \qquad \text{...from circuit behaviour}$$
$$V_D = -E - I_D\,R = -E$$
$$V_R = -I_D R = 0\,\text{V}$$

Thus, our diode circuit is simplified to the circuit shown below



Note that $I_R = -I_D = 0\,\text{A}$.

Example 4: Consider the circuit below and find I_1, V_o, I_{D_1} and I_{D_2} with $V_{D(ON)} = 0.7\,\text{V}$ and $D_1 \equiv D_2$.



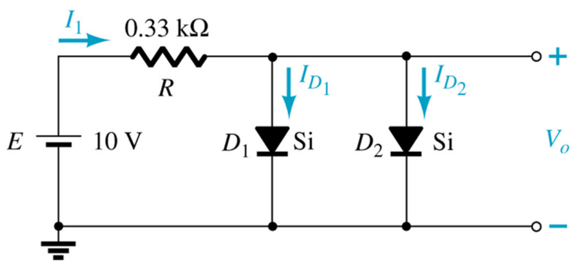
Solution: First we need to determine the state of the diodes (i.e., ON or OFF). As the diodes are parallel, we let us make the following definitions

$$V_D = V_{D_1} = V_{D_2}$$
$$I_D = I_{D_1} + I_{D_2} = I_1$$

So, let us write down the KVL equation and obtain V_D

$$V_D = E - I_D\,R = 10 - 0.33k\,I_D$$

From the equation above, $V_D|_{I_D=0} = 10 \geq V_{D(ON)}$. So, both diodes are ON.



Thus,

$$V_{D_1} = V_{D(ON)} = 0.7\,\text{V} \quad \text{...from circuit behaviour}$$
$$V_{D_2} = V_{D(ON)} = 0.7\,\text{V} \quad \text{...from circuit behaviour}$$
$$V_o = V_D = 0.7\,\text{V}$$
$$I_1 = \frac{E - V_D}{R} = \frac{10 - 0.7}{0.33k} = 28.18\,\text{mA}$$
$$I_{D_1} = I_{D_2} = \frac{I_1}{2} = 14.09\,\text{mA} \quad \text{...as } D_1 \equiv D_2$$

Homework 1: What will happen if D_2 is replaced by a Germanium diode and D_1 remains as a Silicon diode?

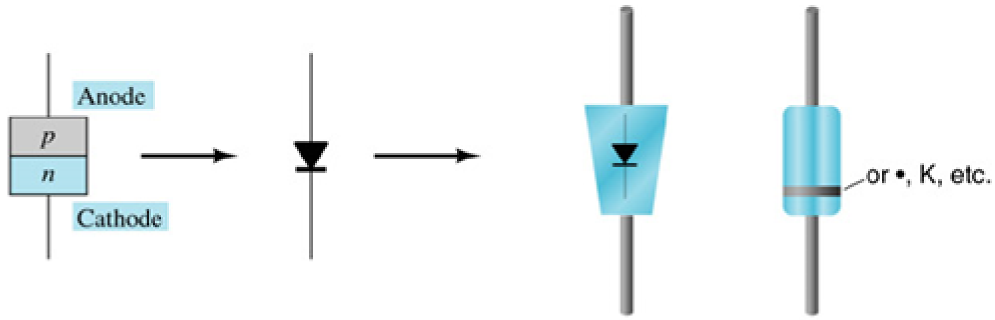
Diode Specification Sheets

Data about a diode is presented uniformly for many different diodes. This makes cross-matching of diodes for replacement or design easier.

Some of the key elements is listed below:

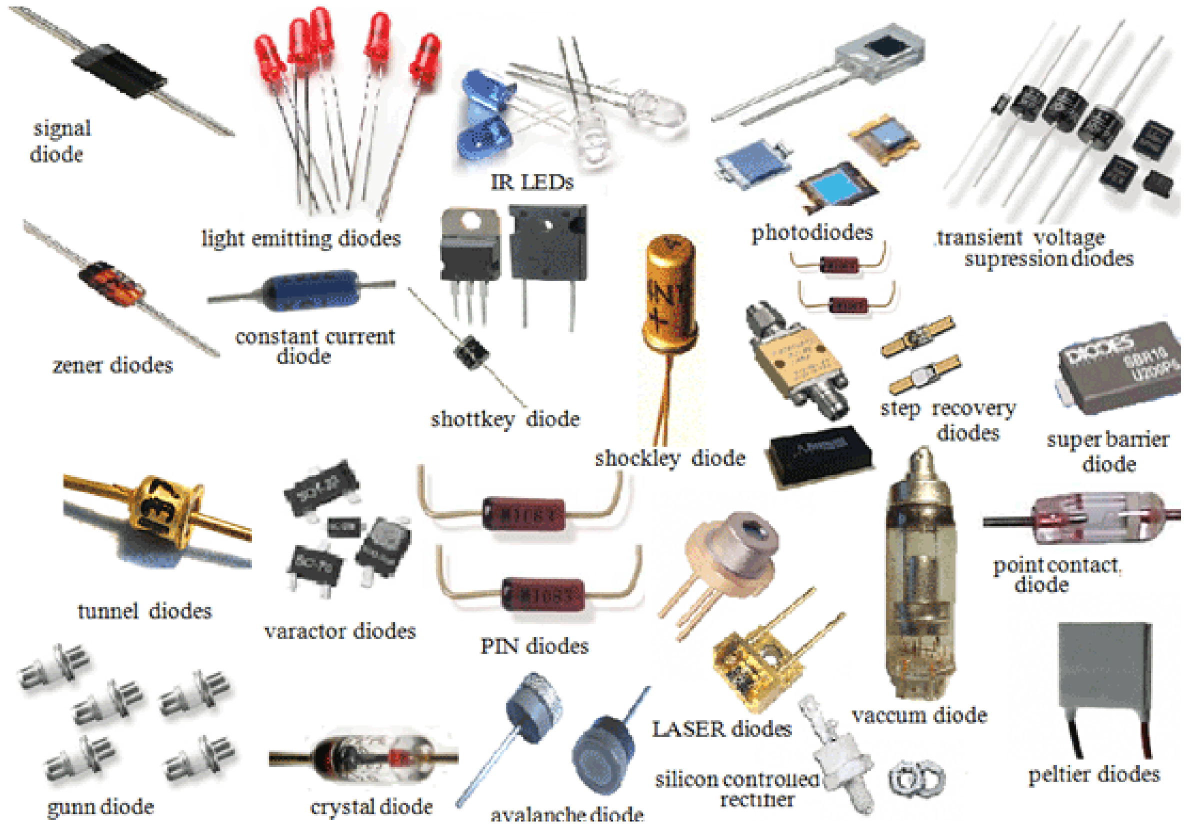
1. V_F: forward voltage at a specific current and temperature
2. I_F: maximum forward current at a specific temperature
3. I_R: maximum reverse current at a specific temperature
4. PIV or PRV or VBR: maximum reverse voltage at a specific temperature
5. Power Dissipation: maximum power dissipated at a specific temperature
6. C: Capacitance levels in reverse bias
7. t_{rr}: reverse recovery time
8. Temperatures: operating and storage temperature ranges

Semiconductor Diode Notation



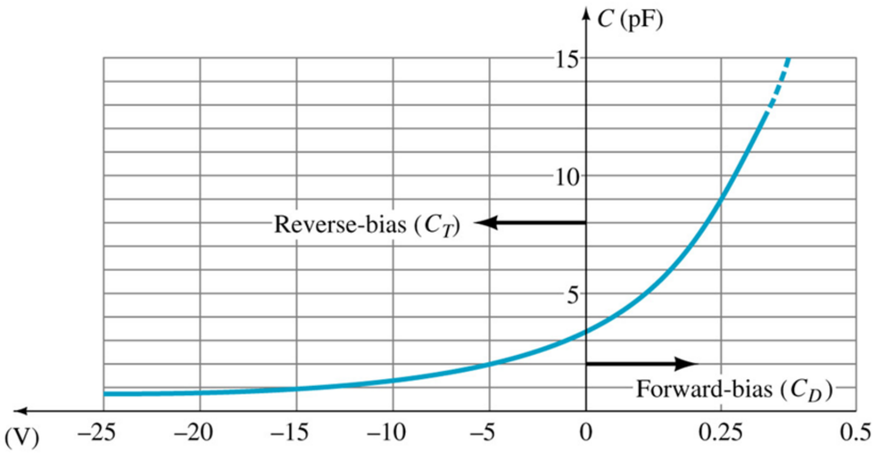
- Anode is abbreviated as A.
- Cathode is abbreviated as K (because the Cathode end of the diode symbol looks like a backwards K).

Examples of some diode types and packagings are shown below.



Types of Diode

Capacitance



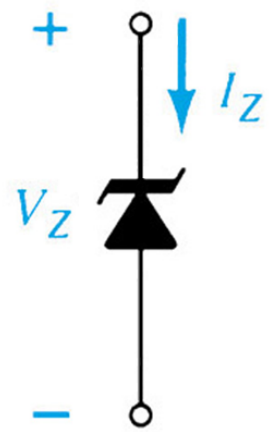
- In **reverse bias**, the depletion layer is very large. The diode's strong positive and negative polarities create capacitance, C_T. The amount of capacitance depends on the reverse voltage applied.
- In **forward bias**, storage capacitance or diffusion capacitance (C_D) exists as the diode voltage increases

Other Types of Diodes

Other types of diodes we like to mention are listed below

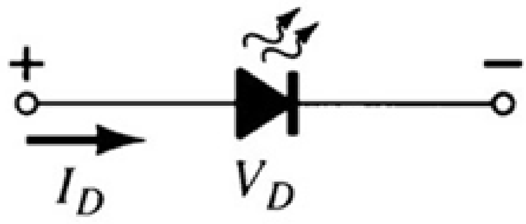
1. Zener Diode
2. Light Emitting Diode

Zener Diode

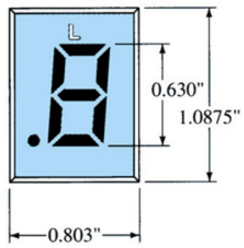


- A Zener is a diode operated in reverse bias at the Peak Inverse Voltage (PIV) called the **Zener voltage** (V_Z).
- Common Zener voltages: 1.8 V to 200 V.
- We are going to cover Zener diodes in more detail later in the course.

Light Emitting Diode (LED)



- This diode when forward biased emits photons. These can be in the visible spectrum.
- The forward bias turn-on voltage is higher, usually around 2-3 V.
- A Litronix 7-segment LED display is shown below



- Relative intensity of each color versus wavelength appears in the figure below.