Introduction to the PN Junction Diode

Note: In this chapter we consider ***conventional current flow.***

The schematic symbol for the pn junction diode the shown in Figure 1. The n-type material is called cathode and the p-type material is called the anode.

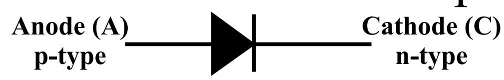


Fig. 1

Note that the schematic symbol looks like an arrow head. The arrow head points in the direction of conventional current flow. A diode conducts when the following conditions are met:

1) The arrow points to the more negative of the diode potentials; that is, the cathode is more negative than the anode.

2) The difference of potential across the diode (from lead to lead) exceeds the barrier potential of the device: 0.7 volts for silicon diode and 0.3 volts for germanium diode.

Examine figure 2.2 in the text on page 24. Note that each diode symbol points to the more negative potential. Note that in each case conventional current flow will be in the direction of the arrow.

A pn- junction diode is reverse biased when the n-type material is more positive p-type material. It will not conduct when the arrow points to the more positive of the diode potentials.

Examine figure 2.3 in the text on page 25. Note that each diode symbol points to the more positive potential therefore each diode is reverse biased.

Diode Models

There are three models of the diode that we need to consider. A model is a representation of a component or circuit that demonstrates one or more of the characteristics of that component or circuit.

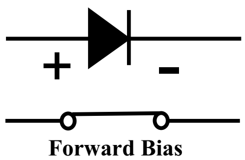
The ***first model*** is the ***ideal diode*** model. This is the simplest model in which the diode is a simple switch that is either closed (conducting) or open (non conducting). This model is used only in the initial stages of troubleshooting where we are considering only a go or no go situation.

The ***second model*** is the ***practical diode*** model. It is a bit more complex than the ideal diode model. The practical diode model includes the diode characteristics that are considered when mathematically analysing a diode circuit and when determining whether or not a given diode can be used in a given circuit.

The ***third model*** is called the ***complete diode*** model. It is the most accurate of the diode models. It includes the diode characteristics that are considered only under specific conditions such as in circuit development (or engineering) or high frequency analysis.

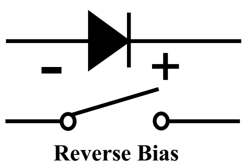
The Ideal Diode Model

The Ideal Diode



When Forward Biased

- The diode will have no resistance
- The diode will have no control over the current through it.
- The diode will have no voltage drop across its terminals.



When Reverse Biased

- The diode will have infinite resistance
- The diode will not pass current.
- The diode will drop the entire voltage across its terminals.

The Ideal Diode acts like a Switch

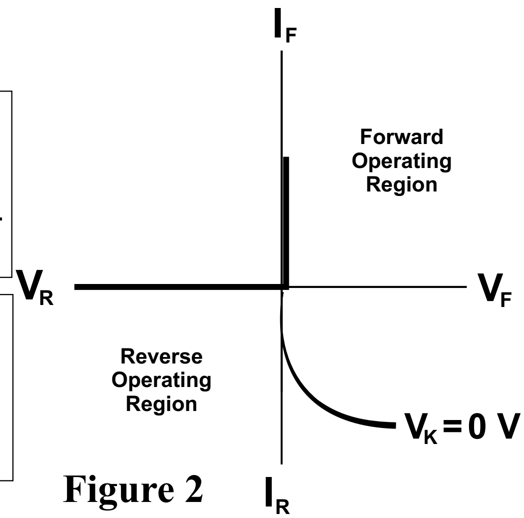


Figure 2

The graph in Figure 2 illustrates the characteristics of the ideal diode model. Diode forward voltage (V_F) and reverse voltage (V_R) are measured along positive and negative x-axes.

Quadrant I of the graph is labelled as the forward operating region because every combination of (V_F) and (I_F) fall within this region of the graph.

Quadrant III of the graph is labelled as the reverse operating region. Here the diode is reverse biased and negative values of voltage (V_R) are being applied to it. Notice that as the reverse voltage (V_R) increases, the reverse current (I_R) remains at zero.

This implies that the reverse biased diode is acting like an open switch, since there is no current through the device, regardless of the applied voltage.

Work through example 2.1 & 2.2 in the text.

The Practical Diode

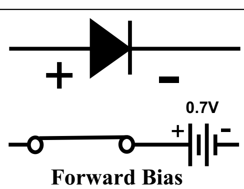
The practical diode considers many of the diode characteristics that must be dealt with on a regular basis. These include ***forward voltage, peak reverse voltage, average forward current***, and ***forward power dissipation***.

Forward voltage, (V_F)

Forward voltage, (V_F) is normally considered in the mathematical analysis of a diode circuit. In the last chapter on the pn junction, we discussed forward voltage. This is the voltage pressure required to overcome the barrier potential and cause the diode to conduct.

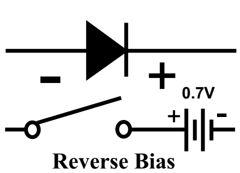
If you look back and Figure 2 (the ideal diode), note that the forward voltage (V_F) is zero volts. This is because, for the ideal diode, we consider the diode to conduct with any value of voltage above zero. The voltage point at which the diode begins to conduct (I_F suddenly increases) is called the knee voltage (V_K). For the ***ideal diode the knee voltage is that zero volts***. For the ***practical diode the knee voltage is 0.7 volts for silicon.*** (See Figure 3). In an actual circuit the V_F may fall between 0.7 volts and 1.1 volts depending on the current through device.

The Practical Diode



Forward Biased Characteristics

- The diode current remains at zero until the knee voltage is reached.
- Once the applied voltage reaches the value of V_K, the diode turns on and forward conduction occurs
- As long as the diode is conducting, the value of V_F is approximately equal to V_K



Reverse Biased Characteristics

- The diode will have infinite resistance
- The diode will not pass current.
- The diode will drop the entire voltage across its terminals.

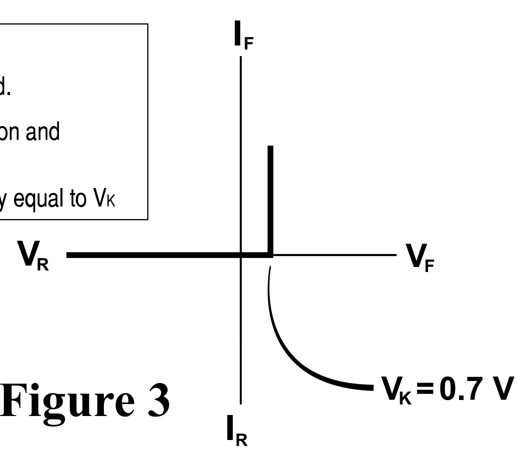


Figure 3

Other Practical Considerations

There are other considerations that are part of the practical diode model.

They are ***peak reverse voltage, average forward current, and forward power dissipation.***

These factors must be considered if a diode were to be replaced in a circuit. All of these characteristics must be considered in order to make a proper choice for a replacement diode.

Peak Reverse Voltage (V_{RRM})

The peak reverse voltage for a diode is the maximum reverse voltage that won't force the diode to conduct. When V_{RRM} is exceeded, the depletion layer may breakdown and allow the diode to conduct in the reverse direction.

Typical values of V_{RRM} range from a few volts to thousands of volts. This value is specified in the spec. sheet for the diode. It must be considered when a replacement diode is required.

If the reverse voltage applied to a diode exceeds V_{RRM}, then the diode will conduct. This current, called the ***avalanche current***, can generate sufficient heat to destroy the diode. The peak reverse voltage is an important parameter (limit). When you are considering whether or not to use a specific diode in a given application, you must make sure that the diodes peak reverse voltage rating is greater than the maximum reverse voltage in the circuit.

The Practical Diode Model

Example:

A circuit has a maximum reverse voltage of 50 V. The replacement diode used here must have at ***peak reverse voltage of greater than 50 volts.*** We generally build in at least a 20 percent safety factor. Using this: What is the minimum V_{RRM} rating that should be used?

$$V_{RRM} = 1.2\ V_{R(pk)} = (1.2)(50V) = 60\ V\ (\text{minimum})$$

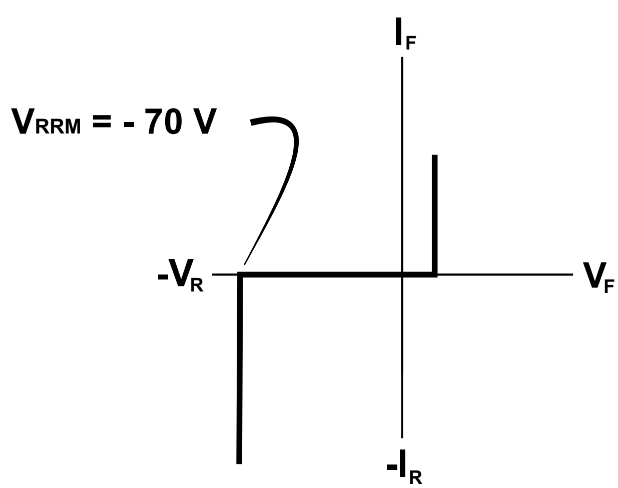
As long as the diode used as the V_{RRM} rating that is equal to (or greater then) 60 V, it will be able to handle minor variations of voltage in the circuit without being driven beyond its reverse voltage limit.

A further explanation is available in section 2.4 in the text.

The effect of V_{RRM} is shown in the diode characteristic curve shown Figure 4. The reverse current (I_R) a shown to be 0 until the value of V_{RRM} (-70V) is reached.

When $V_R > V_{RRM}$ the value of I_R increases rapidly as the depletion layer breaks down.

Normally, when pn junction is forced to conduct in the reverse direction, the device is destroyed.



Peak Reverse Voltage (V_{RRM})

Figure 4

The Practical Diode Model

Work through Examples 2.3, 2.4, 2.8 in the text

Average Forward Current (I_o)

Average forward current rating of a diode is the maximum allowable value of dc forward current.

For example, the 1N4001 diode has an average forward current rating of 1 A. This means that the dc forward current through the diode must never exceed 1 A. If the dc forward current to the diode is allowed to exceed 1 A, the diode may be destroyed from excessive heat.

The average forward current rating is a parameter followed on the spec. sheet for the component. This is another factor that must be considered when replacing a diode.

Work through Examples 2.9 in the text

Forward Power Dissipation $P_{D(MAX)}$

Many diodes have a forward power dissipation rating. This rating tells us the maximum possible power dissipation of the device when it is forward biased. Power is measured in watts.

To find the power that will be dissipated by the component simply multiply the voltage across it times the current through it.

$$P = IV$$

Work through Examples 2.10 in the text

Finding Average Forward Current from $P_{D(MAX)}$

Often, diodes specification sheets give forward power dissipation ratings instead of average forward current ratings. Average forward current for diode can be followed using the following formula:

$$I_O = \frac{P_{D(max)}}{V_F}$$

Work through Example 2.11 Page 38 in the text

Summary

If there are three main parameters that must be considered when replacing a diode:

1) Is the V_{RRM} rating of the replacement diode at least 20 percent greater than the maximum reverse voltage of the circuit?

2) Is the average forward current rating of the replacement diode at least 20 percent greater than the average (dc) value of I_F in the circuit?

3) Is the forward power dissipation rating of the replacement diode at least 20 percent greater than the value of P_F in the circuit?

The Complete Diode Model

This diode model most accurately represents the true operating characteristics of the diode

Two factors make this model so accurate:

1/ Bulk Resistance R_B

This is the natural resistance of the diode p- type and n- type materials

2/ Reverse Current I_R

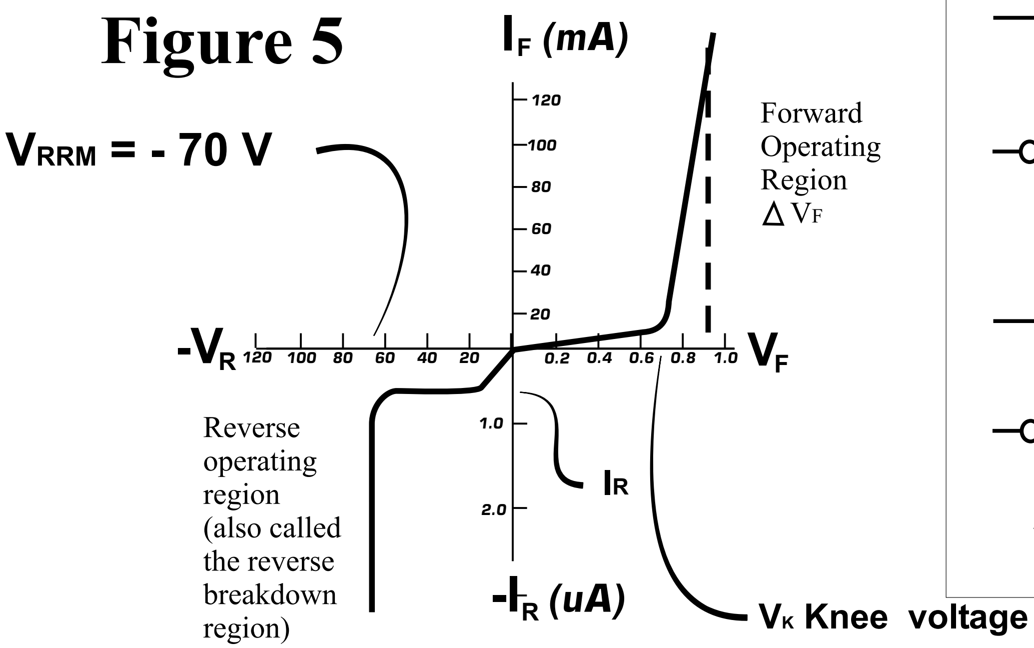
Reverse current is made up of two independent currents ***reverse saturation current, I_S and surface leakage current I_{SL}***

$$I_R = I_S + I_{SL}$$

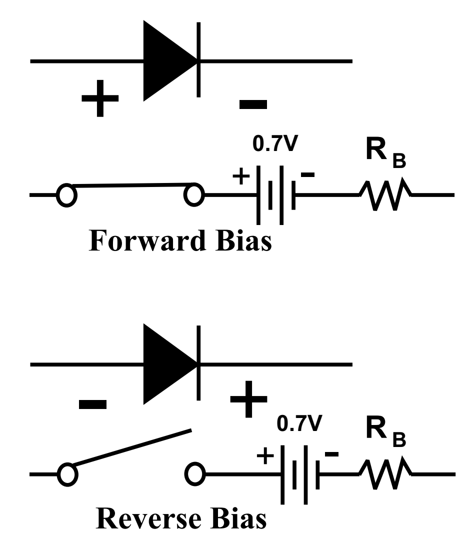
Reverse Saturation Current is the current caused by thermal activity in the two diode materials. It is strictly a function of temperature and it is not affected by the amount of reverse bias applied to the diode. I_S accounts for the major portion of reverse current.

Surface leakage Current is the current that is present on the surface of the diode. This current will increase with the increase in reverse bias.

Figure 5



Complete Diode Model Curve



$$V_F = V_B + I_F R_B$$

The Complete Diode Model

Bulk Resistance R_B

Bulk resistance is natural resistance of the diode p-type and n-type materials. The effect of bulk resistance on the diode operation can be seen in the forward operation region of the curve. See Figure 5. Note that V_F is not constant, but rather, varies with the value of I_F. The line in the forward region is sloped away from vertical. This slope is caused by the bulk resistance.

Look at Figure 6. Note that the bulk resistance R_B, is inside the diode. The forward voltage (V_F) is measured across the diode as shown. As the forward current through the diode increases, a small voltage will develop across R_B. This voltage across R_B will vary with the current. The forward voltage V_F is the barrier voltage (0.7 volts) plus the small voltage developed across R_B ($I_F R_B$)

The bottom-line is that V_F will increase with current. In Lab 4, you will forward bias a diode at different increasing current levels and measure the value of V_F. You should find that as the forward current increases, so does the forward voltage increase slightly.

The change that you see in V_F is caused by the voltage developed across the bulk resistance.

Example 2.12 on page 41 shows this.

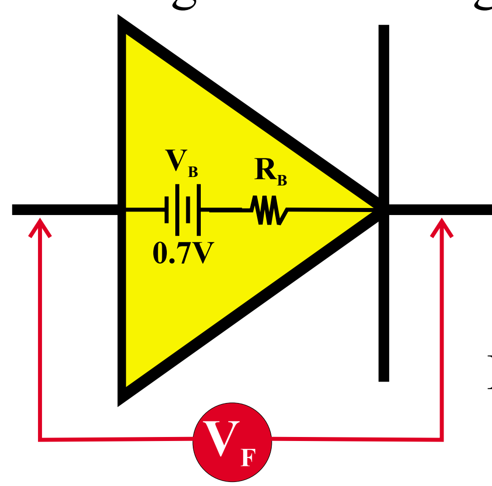


Figure 6

$$V_F = V_B + I_F R_B$$

Diode Equivalent Circuit

Bulk Resistance and Circuit Measurements

With the practical model, we assumed that the value of V_F (silicon) to be 0.7 V. This figure works well for circuit calculations and analysis, but you will find that measured values of V_F are generally somewhere between 0.7 and 1.1 V.

A diode used in low current applications usually has very little voltage developed across its bulk resistance. The value of V_F in this case will be close to 0.7 V.

A diode used in high current applications will likely have a relatively large voltage developed across its bulk resistance. This causes it a value of V_F that is closer to 1.1 V.

For most routines circuit measurements, using the approximate value of 0.7V is acceptable because the exact value of V_F isn't critical. However in circuit development or engineering applications, the circuit designer may need to predict very accurately the value of V_F in circuit. This is when the complete diode analysis is used and the formula for V_F is:

$$\mathbf{V_F = 0.7\ V + I_F R_B}$$

Reverse Current and Circuit Measurements

The ideal model and the practical model assumed in the value of I_R is zero. We know, that a small amount reverse current occurs in a diode circuit. This reverse current causes the very slight voltage to be developed across any resistance in the circuit. In lab 4, you will calculate this current by measuring the voltage that it develops across a resistance. An example of this is shown in the text on page 42. Please read and understand this method.

The Complete Diode Model

Other Factors considered in the Complete Model

Diode Capacitance

As we will study later, a capacitor is created by placing an insulator between two spaced conductors. When a diode is reverse biased, a depletion layer is formed that acts like an insulator between the two semi-conductor materials.

The reverse biased diode has a measurable ***junction capacitance*** that is usually very small. (in pF). This is usually not a concern in low frequency circuits. In high frequency circuits, this capacitance is very important because it can affect circuit performance.

A ***varactor diode*** is a type of diode that is made to take advantage of this capacitance effect. It is commonly used to tune television channels in the tuner of TV sets. We vary the capacitance of the diode by varying the reverse bias across the diode.

Diffusion Current

With the practical model, we said that forward current (I_F) is zero until the knee voltage (V_K) is reached. In the complete model, we consider the ***diffusion current.*** If you look at figure 7, you will note that, below the knee voltage the forward current (I_F) does not instantly drop to the zero point.

This small current is called the ***diffusion current***. When (V_F) goes below the barrier potential of the diode, the depletion layer begins to form. At this point, the depletion layer is nowhere near its maximum width. Because of this, it has not reached its maximum resistance. The depletion layer only reaches its maximum resistance when it is that its maximum width and this only happens when the diode is reverse biased.

The Complete Diode Model

This means that as long as there is some forward voltage (below 0.7 V) there will be as small amount of forward current called diffusion current.

When the diode is switching from forward bias to reverse bias, the diffusion current will last only is long as it takes the depletion layer to form. This is generally a few milliseconds or less.

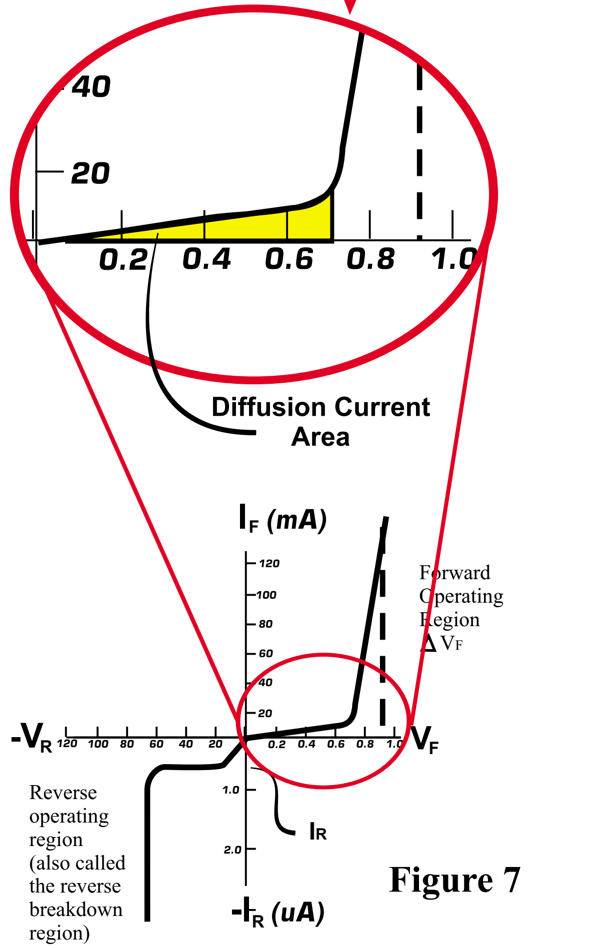


Figure 7

Complete Diode Model Curve Area Showing Diffusion Current

Please read:

- "Temperature Effects on Diode Operation"
  Pages 43 to 45 in the text

- Section 2.6 Diode Specification Sheets
  Pages 46 to 52 in the text

The Zener Diode

The zener diode is designed to work in the reverse breakdown region of its characteristic curve. A pn junction diode operated in this region is usually destroyed by the excessive current and heat that it produces. This is not the case for the zener diode.

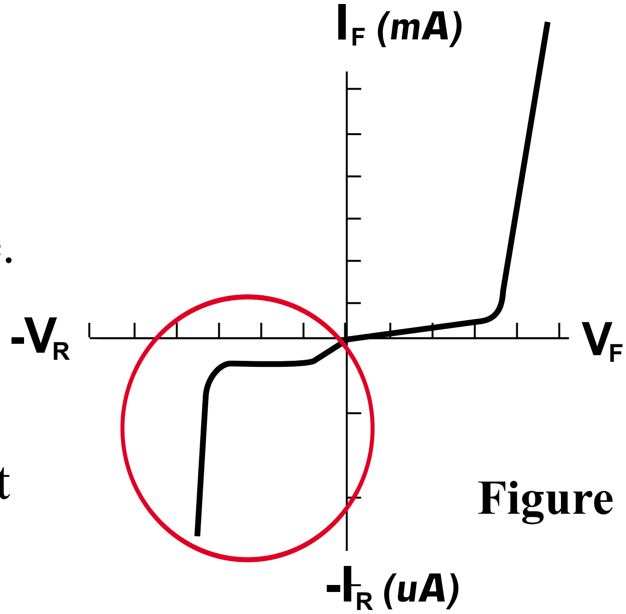


Figure 8

Typical Diode Curve Area of Operation for the Zener Diode

The forward current characteristics of the zener diode are similar to the pn junction diode, however the zener diode is not used in the forward region.

Figure 8 shows a typical diode curve and shows the area of operation for the zener diode.

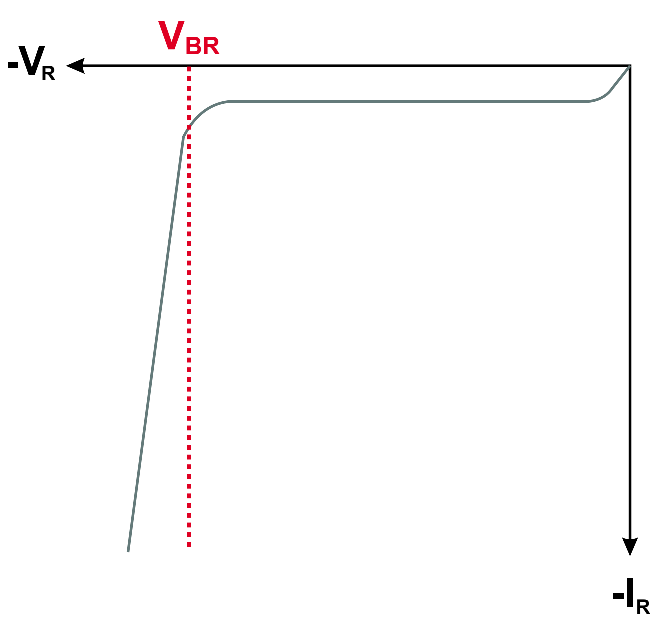


Figure 9 **Zener Diode Reverse Breakdown Characteristics**

Figure 9 shows the reverse breakdown characteristic curve. Two things happen when the reverse breakdown voltage, (V_{BR}) is reached:

1) The diode current increases dramatically.

2) The reverse voltage across the diode V_R remains relatively constant.

This means that the voltage across the diode is relatively constant over a wide range of device current values. This makes the zener diode a good voltage regulator. A voltage regulator is the circuit designed to maintain a constant voltage regardless of minor variations in load current or input voltage.

The zener diode is used for its reverse operating characteristics and ***conventional current flows against the arrow*** as shown in figure 10. For this device current flows when the cathode is more positive than the anode.

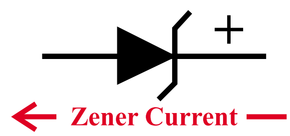


Fig.10

When the zener is operating in the reverse operating region, the voltage across the device will be nearly constant and equal to the zener voltage (V_Z) rating of the device. Zener diodes have a range of V_Z ratings from about 1.8V to several hundred volts. They also have power dissipation ratings of between 500 mW and 50W.
The zener rating always tells you the approximate voltage across the device when it is operating in the reverse breakdown region.

Zener Diode Breakdown

There are two types of reverse breakdown, ***avalanche breakdown*** and ***zener breakdown***.

Zener Breakdown

Zener breakdown occurs at much lower values of V_R than does avalanche breakdown. The heavy doping of the zener diode causes the device to have at much narrower depletion layer. As a result, it only takes a small reverse voltage of typically 5V or less to cause the diode to go into breakdown.

Zener diodes with a V_Z rating of 5V or less experience zener breakdown while those having a V_Z rating of greater than 5V usually experience avalanche breakdown.

Avalanche Breakdown

Avalanche breakdown is when the reverse bias voltage across the diode exceeds the depletion layers ability to oppose it.

The electrons have enough energy now across the depletion layer. In an ordinary pn junction diode, the diode is usually destroyed by the excessive heat that the avalanche current creates.

It should be noted that in the case of the ***zener diode, avalanche breakdown does not destroy the diode*** provided that ***the maximum allowable current is not exceeded.***

Zener Operating Characteristics

Figure 11 showed how a zener diode maintains the near constant reverse voltage for a range of reverse current values. Note the three currents listed:

I_{ZK} This is the minimum value of I_Z required to maintain voltage regulation. This is called the ***zener knee current***. When a zener is used as a voltage regulator, the current through the diode must never be allowed to drop below I_{ZK}

I_{ZT} This is the zener test current. It is the current level at which the V_Z rating of the diode was taken. For example, if the diode has $V_Z = 9.1V$ and $I_{ZT} = 20$ mA, this means that the diode has a reverse voltage of 9.1V when the test current was 20 mA. At other currents the value of V_Z will vary slightly above or below the rated value of 9.1V.

I_{ZM} This is the maximum allowable value of I_Z. Currents above this value will damage or destroy the diode.

Design Note

If you need to have a zener voltage that is as close to the nominal (rated) value of V_Z as possible, then design the circuit to have the zener current as close to I_{ZT} as possible. The further your circuit current is from I_{ZT}, the further V_Z will be from its rated value.

Zener Impedance Z_Z

Zener impedance (Z_Z) is the zener diode's opposition to a change in current. It is measured for a specific change in zener current around I_{ZT}. Figure 12 is an example for finding zener impedance.

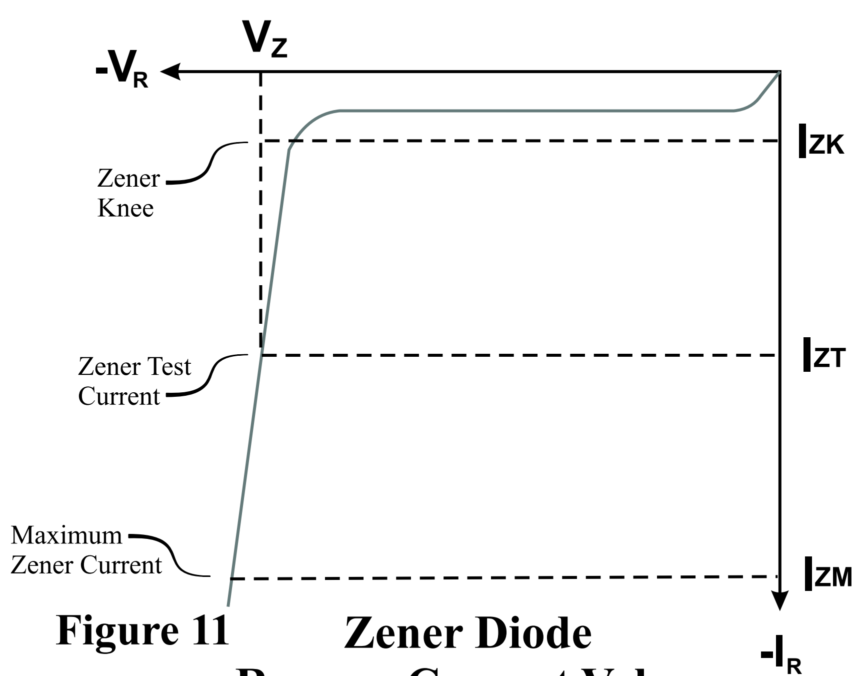


Figure 11 Zener Diode Reverse Current Values

Finding Zener Impedance Z_Z

If we were to look up the specs for a 1N746 to 1N759 series of zener diodes, we would find the following test conditions for measuring Z_Z:

I_{ZT} = 20 mA I_{zt} = 2 mA

I_{ZT} is the test current. The name plate value for the zener diode is taken at this current of 20 mA. To find the value of Z_Z, we are really trying to find the slope of the line between V_1 and V_2 in fig. 12.

Determining Zener Impedance

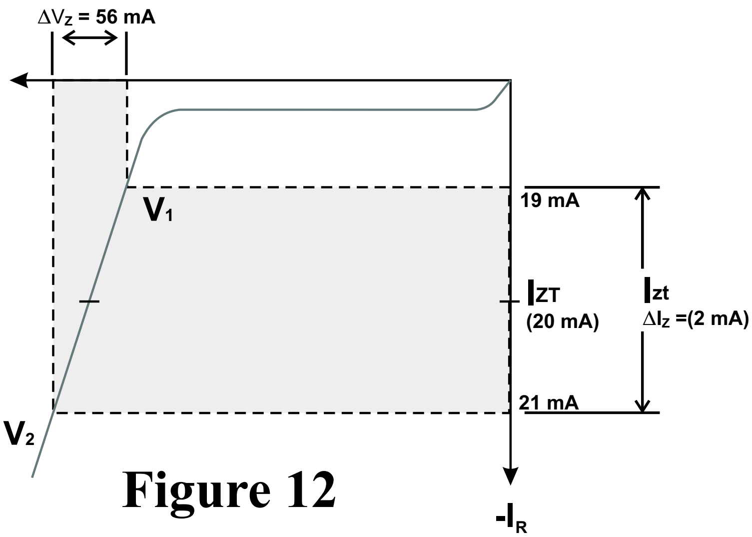


Figure 12

Z_Z ***Zener Impedance*** is the Zener Diode's opposition to a change in current.

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} \quad \Big| \; \Delta V_Z = \text{the change in } V_Z$$

$$Z_Z = \frac{56\text{ mV}}{2\text{ mA}} = 28\ \Omega$$

To do this we will lower than current from 20mA to 19mA and measure the new value of V_Z. Then we will raise the current to 21 mA and again measure the new value of V_Z.

Now we find the change in V_Z (V_Z). In the example it is 56 mV.

Now we find the change in I_Z ($_Z$). In the example it is

21mA - 19mA = 2 mA

Using Ohm's law -- find $Z_{Z.}$

The 2 mA found above is given on the spec. sheet as I_{zt}

Impedance is an ac value. This is because we had to use changing values to find it.

Static Reverse Current (I_R)

This is the reverse current through the diode when V_R is less V_Z. This is generally a very low value. Figure 13 shows the area where static reverse current exists.

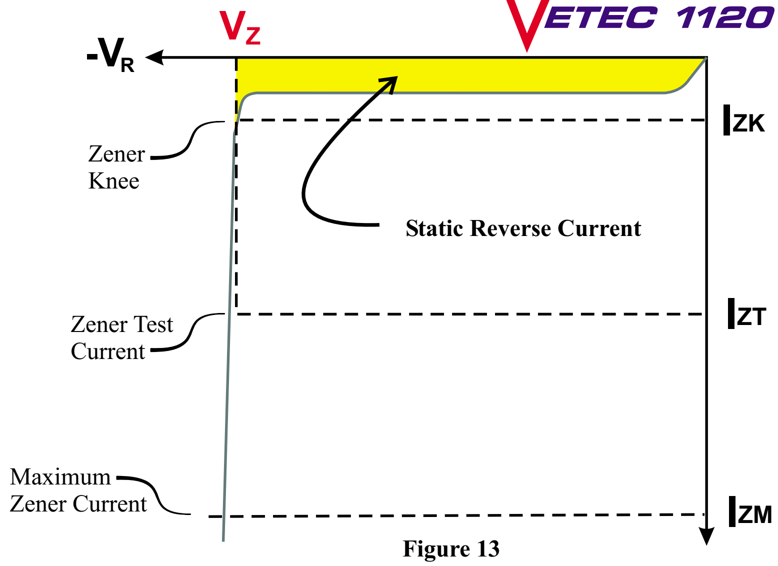


Figure 13
Zener Diode Static
Reverse Current Values

Zener Equivalent Circuits

There are two models or equivalent circuits for the zener diode.

Ideal Model

This model simply considers the zener diode to be equivalent to a voltage source V_Z. Figure 14 (a) shows the model. Note that the voltage source opposes the applied circuit voltage.

The Practical Model

This model includes Z_Z. It appears as a resistor as shown in Figure 14 (b). This model is used primarily for predicting the response of a diode to a change in circuit current.

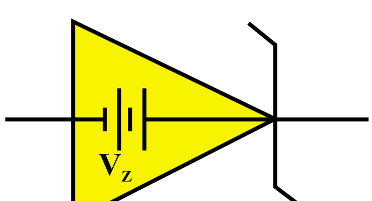


Fig. 14 (a) Ideal Zener Model

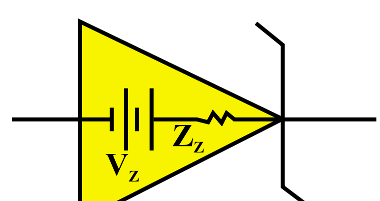


Fig. 14 (b) Practical Zener Model

Read chapter 2.8 on Zener spec. sheets

Light Emitting Diode (LED)

A LED emits light when forward biased. When a LED conducts, electrons pass from the conduction band of the N-type material to the conduction band of the P-type material.

These electrons immediately drop into holes in the lower energy valence shell. The electrons give off energy in the form of light when they move into the valence shell.

LED's have similar characteristics to those of a standard PN junction diode except they tend to higher forward voltages V_F and lower reverse breakdown voltages V_{BR}. The forward voltages typically range from 1.2 to 4.3 volts while the reverse breakdown voltages range from 3 to 10 volts.

Example

The LED in the circuit below has a forward voltage rating of 1.8 to 2.0 volts. It has a maximum current rating of 12 mA. Calculate the series resistance so that the LED current does not exceed 80% of the maximum current rating.