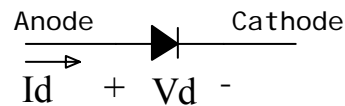


Semiconductor Devices  
Non-linear Devices  
Diodes

Introduction.

The diode is two terminal non linear device whose I-V characteristic besides exhibiting non-linear behavior is also polarity dependent. The non-linear, and polarity characteristics of the diode make for a very interesting and useful device albeit at the expense of added complexity of circuit design and analysis.

The basic circuit symbol of the diode is shown on Figure 1. Unlike the resistor, whose two terminal leads are equivalent, the behavior of the diode depend on the relative polarity of its terminals.



**Figure 1. Diode circuit model**

The conventional voltage polarity across the diode terminals and the current direction through the diode are also indicated on Figure 1.

Depending on the polarity of the voltage  $V_d$  the diode is said to be:

**Forward Biased**, ( $V_d > 0$ ), Anode voltage is greater than the Cathode voltage, or

**Reverse Biased**, ( $V_d < 0$ ), Cathode voltage is greater than the Anode voltage.

## Diode Models.

### Ideal Diode model

Consideration and analysis of the ideal diode, gives us the opportunity to conceptualize the fundamental characteristics of these non-linear devices and to assist us in the analysis of circuits containing diodes.

Of course the discussion of device modeling refers to the mathematical/graphical representation of the current/voltage ( $I$ - $V$ ) characteristic of the device. The  $I$ - $V$  characteristic and the symbol of the ideal-diode is as shown on Figure 2.

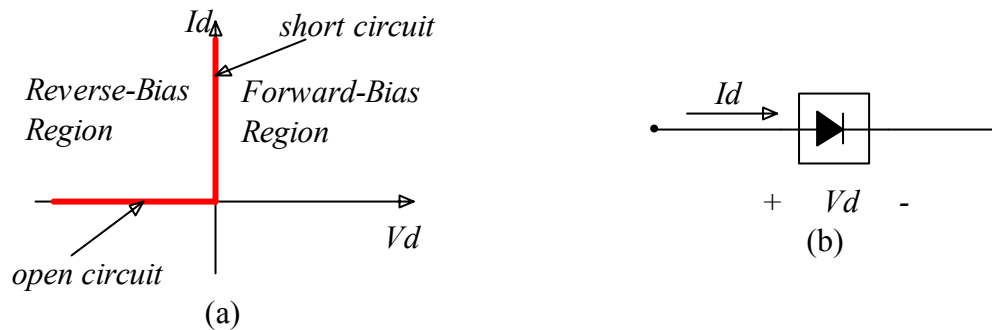


Figure 2.  $I$ - $V$  characteristic (a) and symbol (b) of the ideal diode.

When a reverse bias voltage is applied the current through the diode is zero. When the current becomes greater than zero the voltage drop across the diode is zero.

The non-linear character of the device is apparent from the examination of Figure 2.

This simplified model gives a global picture of the diode behavior but it does not represent important details of this element. Next we discuss the real (full) model of a diode

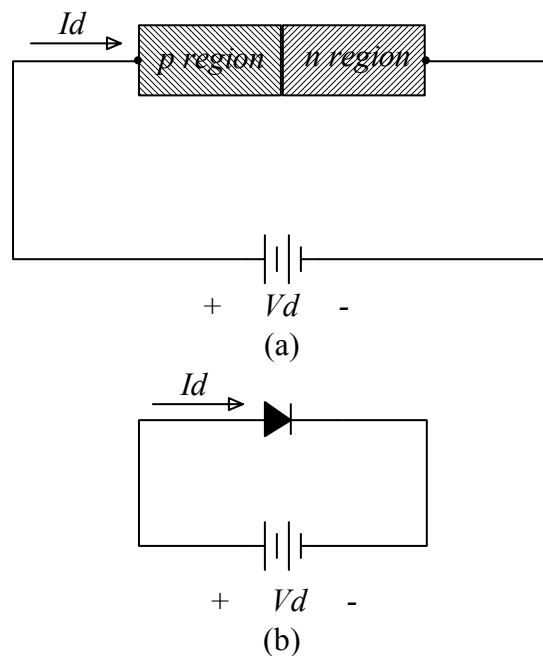
## Full diode model

The diode is a semiconductor device constructed from silicon or other elements from column IV of the periodic table. These materials like Si and Ge are poor conductors of electricity. By doping Si with small amounts of an element from column III (eg. Boron – B) or column V (e.g. phosphorous – P) the conductivity greatly increases. The change in conductivity is associated with the freedom of electrons to move through the material.

The electrons in Si are tightly bound because of the crystal lattice structure. Adding for example phosphorous (from column V) adds another electron to the crystal structure. This “extra” electron is not required to maintain the crystal structure and thus it has considerable freedom to move from site to site within the material. Materials doped with elements in column V are known as “n type semiconductors” indicating the freely moving negative charge – the electron.

If Si is now doped with elements from column III (Ba, Al, Ga) the crystal structure has a deficit of one electron. This deficit of electrons looks like a net positive charge and it is called a “hole”. Electrons within the material can easily move to fill this “hole” leaving behind new holes at the places where they started from. The creation and thus the motion of these holes looks like a flow of a net positive charge. Therefore, materials doped with elements from column III are known as “p type semiconductors” indicating a net positive charge – the hole.

A diode is constructed by fabricating p and n regions in Si as shown schematically on Figure 3(a). The symbol of the diode and the corresponding arrangement of the p and n regions is shown on Figure 3(b). The boundary between the p and the n regions is called the p-n junction.



**Figure 3**

The mathematical function that describes the relationship between the voltage  $Vd$ , and the diode current  $Id$  of a diode (the full model) is,

$$Id = Is \left[ \exp\left(\frac{Vd}{V_T}\right) - 1 \right] \quad (1.1)$$

where the parameters  $Is$  and  $V_T$  are constants characterizing the diode.  $Is$  is called the reverse saturation current and it is independent of the diode voltage  $Vd$ . For silicon diodes  $Is = 10^{-12}$  A or less. The parameter  $V_T \equiv \frac{kT}{q}$  ( $k$  = Boltzmann's constant,  $T$  = the temperature and  $q$  = the electronic charge) is called the thermal voltage. At room temperature  $V_T = 26$  mV.

A typical  $Id$  versus  $Vd$  relationship for a silicon diode is shown on Figure 4. The current increases exponentially with the voltage. A small change in the voltage increases the current by orders of magnitude as may be seen from Figure 5 where the  $I-V$  plot is presented in a logarithmic scale. Note that we have drawn a vertical line at  $Vd=0.7$  Volts to indicate the relative insensitivity of the voltage drop across the diode for large currents. We will use this feature to develop a simplified model of the diode later on.

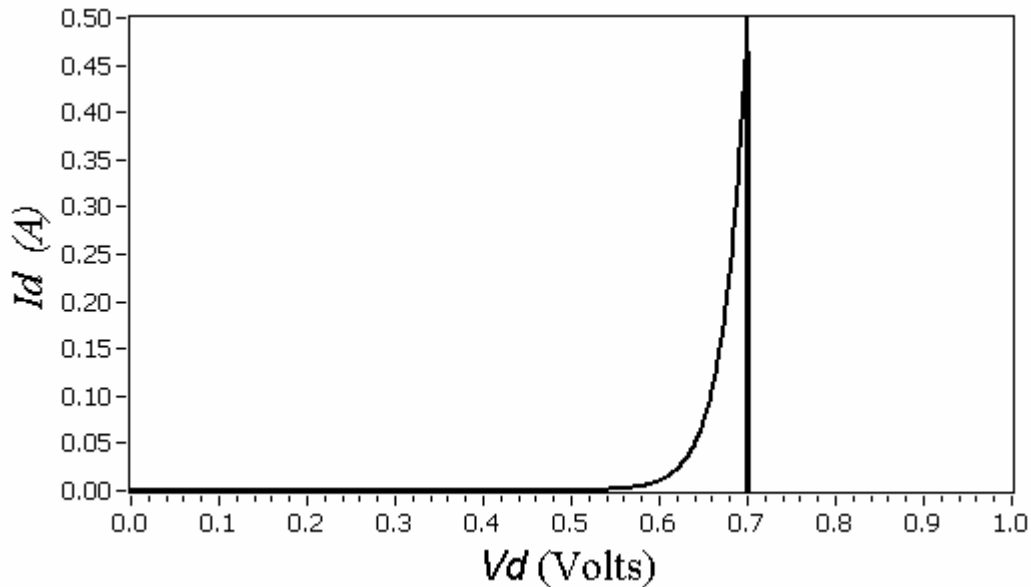


Figure 4. Typical  $I-V$  characteristic of a Silicon diode.

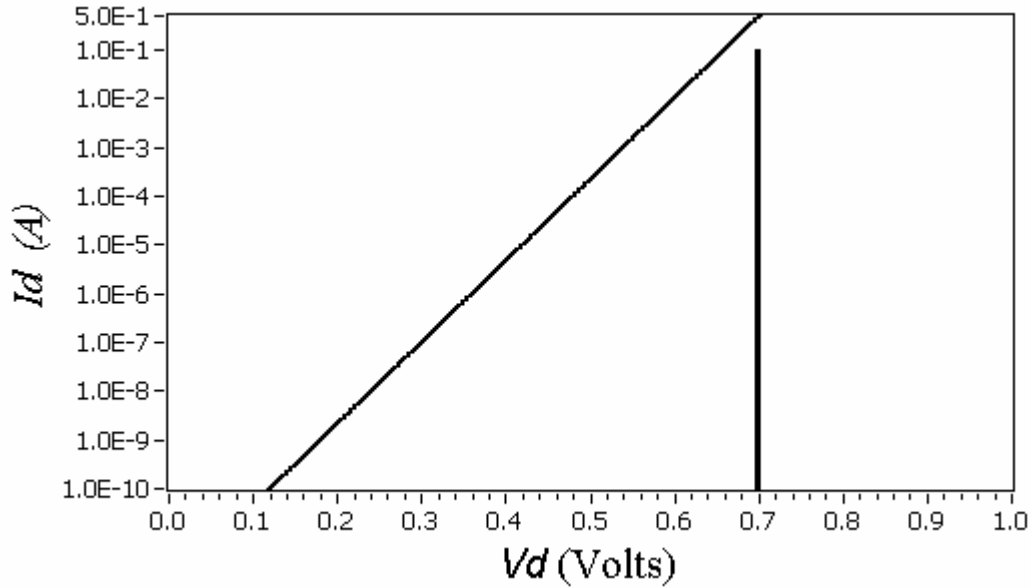


Figure 5. Semi-log plot of typical  $I$ - $V$  characteristic of a Silicon diode.

For bias voltages less than 100mV the current is less than  $10^{-11}$  A and may be neglected in most, but not all, applications. Also for  $V_d > 200$  mV the mathematical expression relating  $I_d$  to  $V_d$  may be simplified by neglecting the  $I_s$  term

$$I_d \cong I_s \exp\left(\frac{V_d}{V_T}\right) \quad (1.2)$$

Figure 6 shows again the  $I$ - $V$  characteristic in a range where the reverse bias characteristics are visible.

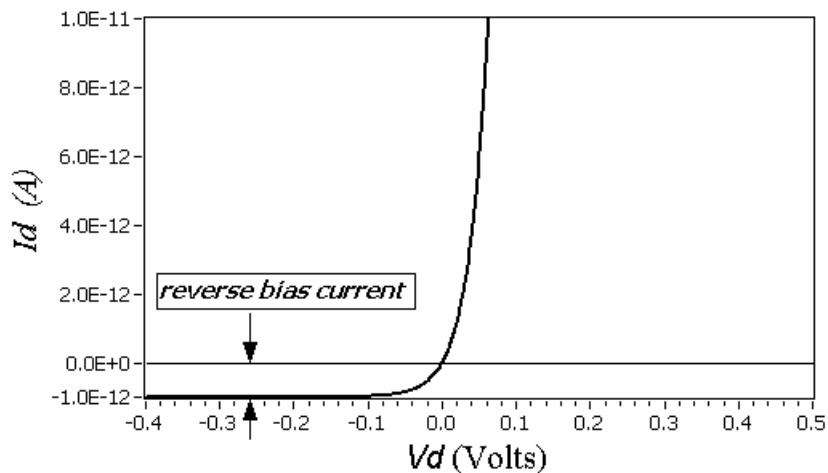


Figure 6. Typical  $I$ - $V$  characteristic of a Silicon diode.

When a reverse biased voltage is applied to a diode (i.e when  $V_d < 0$ ) the behavior of the diode exhibits some interesting characteristics. First if the bias voltage is small then the current flowing through the diode is the reverse bias current  $I_s$ . When the reverse bias voltage reaches a certain value ( $V_b$ ), the electric field generated across the junction results in a very large reverse bias current. This phenomenon is called **breakdown** and the corresponding voltage at which it occurs is called the **breakdown voltage** ( $V_b$ ) as shown on Figure 7. (The graph shown on Figure 7 does not represent the characteristics of a real diode. It is presented for the visual demonstration of the breakdown region only.) For silicon diodes the breakdown voltage is in the range of 50-200 Volts. Care must be taken when designing circuits containing diodes not to exceed the breakdown voltage.

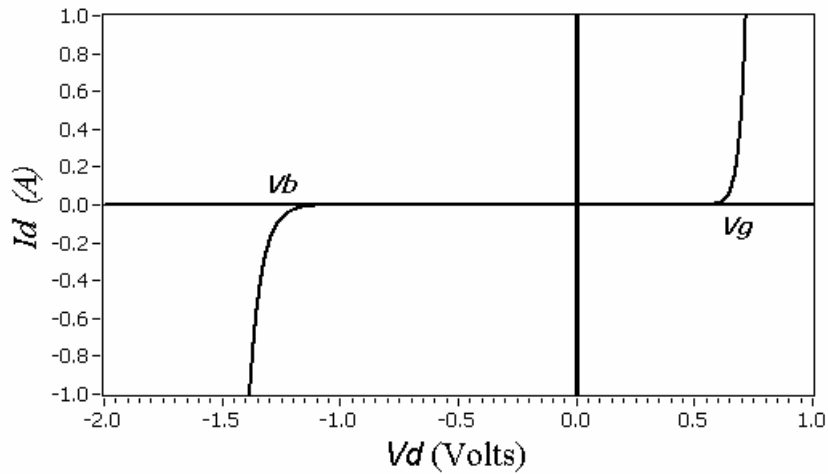
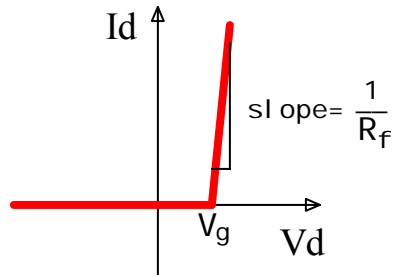


Figure 7

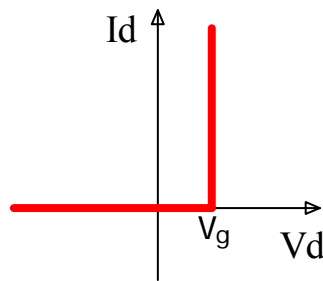
## Offset voltage model

The exponential dependence of  $I_d$  on  $V_d$  results in a highly non-linear system but it also gives us the opportunity to construct a simpler, albeit still non-linear, model for the diode. Such a model is shown graphically on Figure 8.



**Figure 8. Piecewise linear approximation model of the diode.**

In this model the voltage  $V_g$  corresponds to 0.7 Volts. The slope of the “vertical” line is very large corresponding to a very small equivalent resistance ( $R_f$ ) for the diode. Since  $R_f$  is very small it may be neglected ( $R_f=0$ , slope= $\infty$ ) resulting in the model shown on Figure 9.



**Figure 9. Offset diode model (0.7 Volt model)**

This is an enhanced version of the ideal-diode model presented earlier (see Figure 2) and it is motivated by the full diode model. This model is called the **offset diode model** (or the 0.7 Volt model). The voltage  $V_g$  is called the offset voltage. For silicon diodes  $V_g=0.7$  Volts and for germanium diodes  $V_g=0.2$  Volts.

## Diode Circuits.

### Half wave rectifier

Let's start with the circuit shown on Figure 10. We will analyze this circuit assuming that the diode is ideal. The input voltage  $V_{in}$  has the sinusoidal form shown on Figure 11.

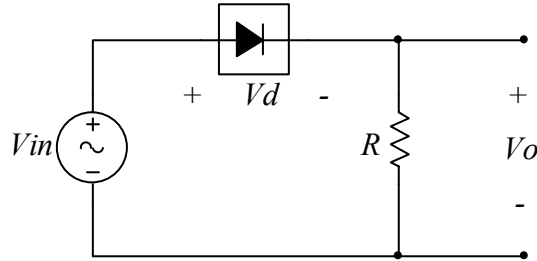


Figure 10. Diode circuit

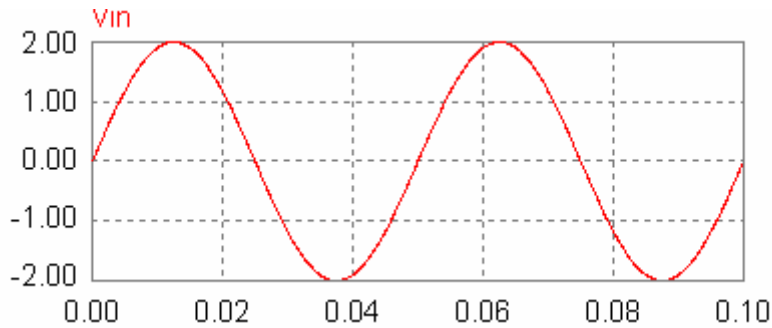


Figure 11. Sinusoidal signal  $V_{in}$

We see that during the time when  $V_{in} > 0$  the diode is forward biased and so the voltage across this “ideal” diode is zero. This observation is also represented by the equivalent circuit shown on Figure 12(a), which clearly indicates that the output voltage  $V_o$  is equal to the input voltage  $V_{in}$ . Similarly during the time when  $V_{in} < 0$ , the diode is reverse biased and so the current flowing through the diode is zero, see equivalent circuit on Figure 12(b), and the output voltage is zero.

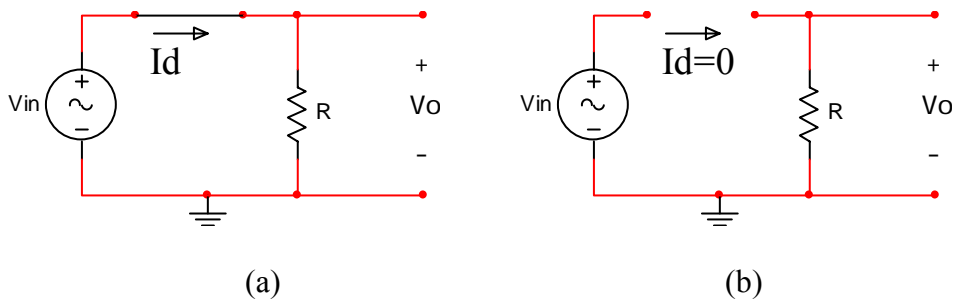
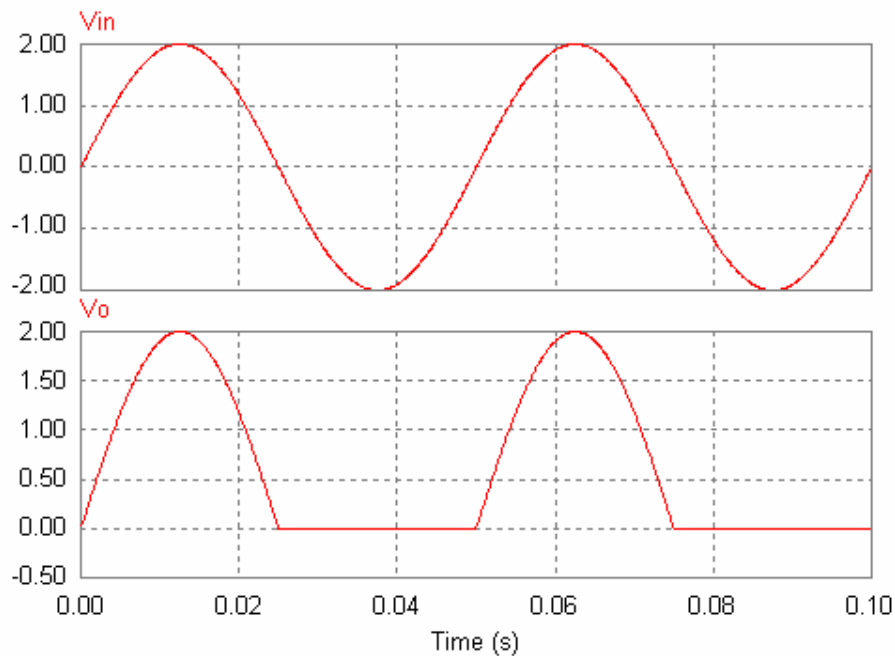


Figure 12. Equivalent circuits for  $V_{in} > 0$  (a) and  $V_{in} < 0$  (b) for the ideal diode



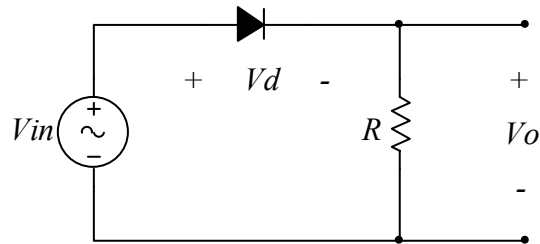
The total response of the circuit to the input signal  $V_{in}$  is shown on Figure 13. Note that the presence of the diode alters the output signal in a profound way: it converts an AC (alternating current) input voltage, whose average value over time is zero, into an output voltage whose polarity does not change over time, and which has a non-zero average value. This type of voltage signal is called DC (direct current) since the direction of the current does not change over time. We have just taken the first step in the design of an AC to DC converter.



**Figure 13. Input signal (top) and equivalent rectified signal (bottom)**

The output signal  $V_o$  is a **rectified** signal of the input  $V_{in}$  and the circuit that generated this signal, Figure 10, is called **Rectifier** circuit. Furthermore, since it passes only half of the input signal it is called a **Half Wave Rectifier Circuit**.

Let's now again analyze the behavior of the rectifier circuit with the offset diode model. The circuit is shown on Figure 14.

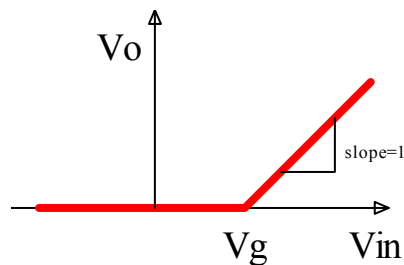


**Figure 14. Half wave rectifier circuit**

Application of Kirchhoff's voltage law (KVL) to the circuit of Figure 14 gives

$$V_o = V_{in} - V_d .$$

The voltage transfer curve for this circuit is shown on Figure 15 and it is derived from the  $I$ - $V$  characteristic of the diode model and Kirchhoff's voltage law.

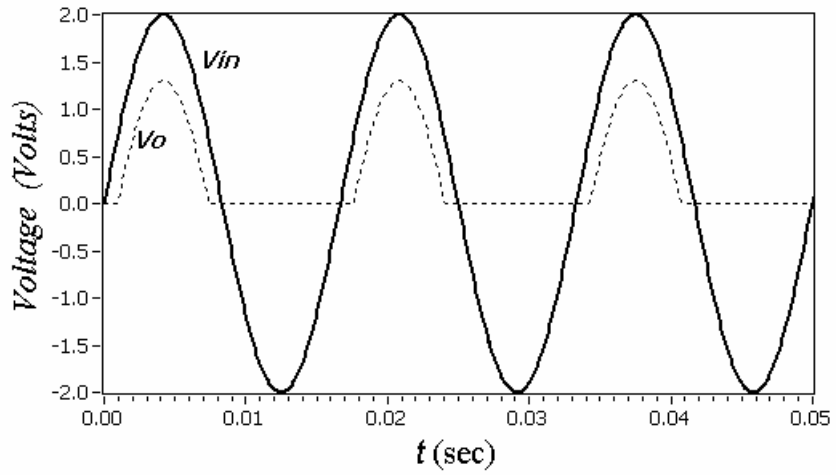


**Figure 15. Voltage transfer characteristic of the rectifier circuit.**

From the voltage transfer curve we observe the following:

- $V_o = V_{in} - V_g$  for  $V_{in} \geq V_g$ ,
- $V_o = 0$  for  $V_{in} < V_g$  (Open circuit)

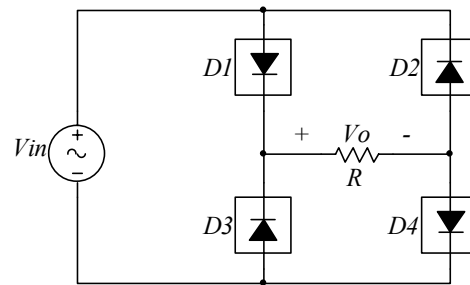
Figure 16 shows the response of the rectifier circuit of Figure 14 for  $V_{in} = 2 \sin(40\pi t)$ . Note the difference between  $V_{in}$  and  $V_o$ . The differences in the output voltage between the full model and the offset diode model are not discernable.



**Figure 16. Source ( $V_{in}$ ) and rectified voltage ( $V_o$ ) for the circuit of Figure 14**

### Full wave rectifier.

Rectifiers are used extensively in the conversion of AC signals to DC. In such a circuit the half wave rectifier is not efficient since it “wastes” half of the signal. A circuit that overcomes this problem is the full wave rectifier which uses four diodes as shown on Figure 17. The diodes are arranged in a bridge configuration. The output voltage is taken across the resistor  $R$ .

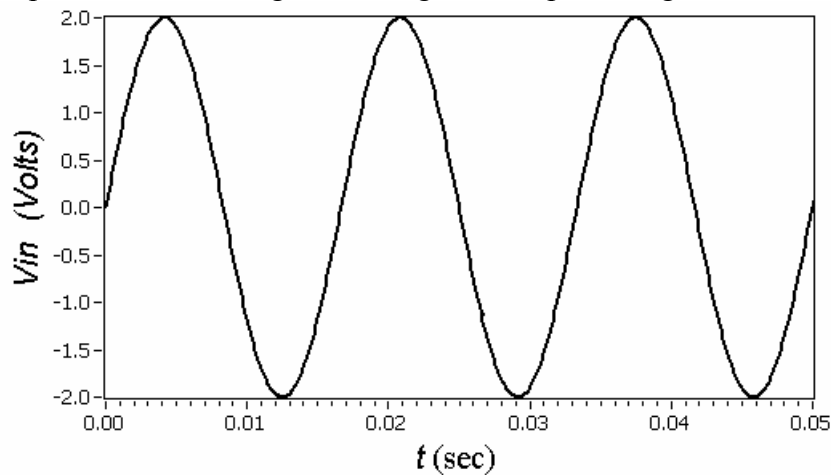


**Figure 17. Full wave rectifier circuit**

First let's consider the response of this circuit using the ideal diode model. We will apply a sinusoidal input signal and detect the output.

Let's consider the example with the sinusoidal input signal  $V_{in}$  shown on Figure 18.

In order to understand the behavior of this circuit we will look at the direction of current flow during the positive and the negative swing of the input voltage.



**Figure 18. Input signal to a full wave rectifier**

When  $V_{in}$  is positive, diodes  $D1$  and  $D4$  are forward biased and diodes  $D2$  and  $D3$  are reverse biased and the direction of the current is shown on Figure 19(a). During the negative part of the cycle, diodes  $D2$  and  $D3$  are forward biased and diodes  $D1$  and  $D4$  are reverse biased and the current flow is indicated on Figure 19(b). Note that the current through the resistor  $R$  is in the same direction during the entire cycle. This is the basis for the behavior of the full wave rectifier circuit.

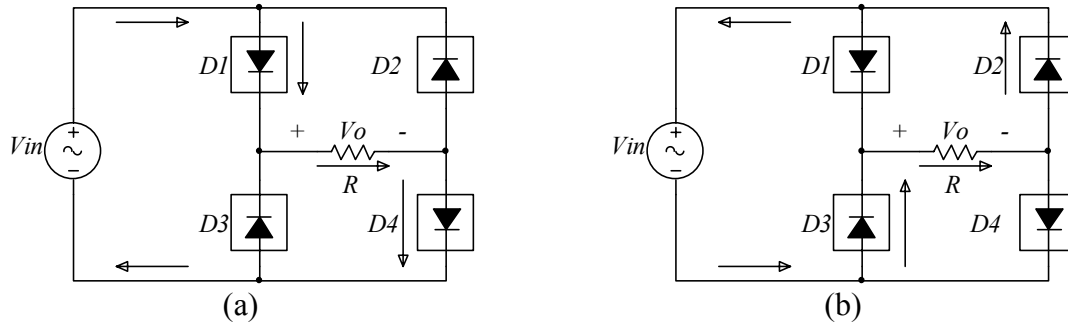


Figure 19.

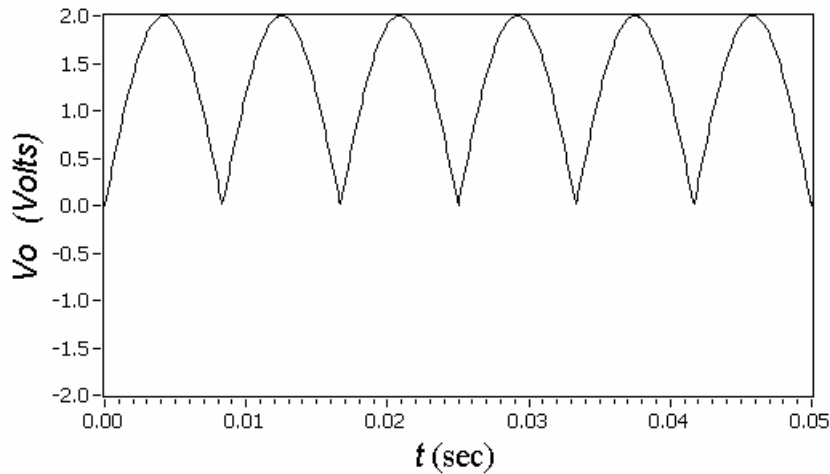


Figure 20. Output signal of a full wave rectifier with ideal diodes.

Now let's consider the more realistic scenario represented by the full diode model. In this case the direction of the current during the positive and the negative cycle is the same as before (see Figure 21).

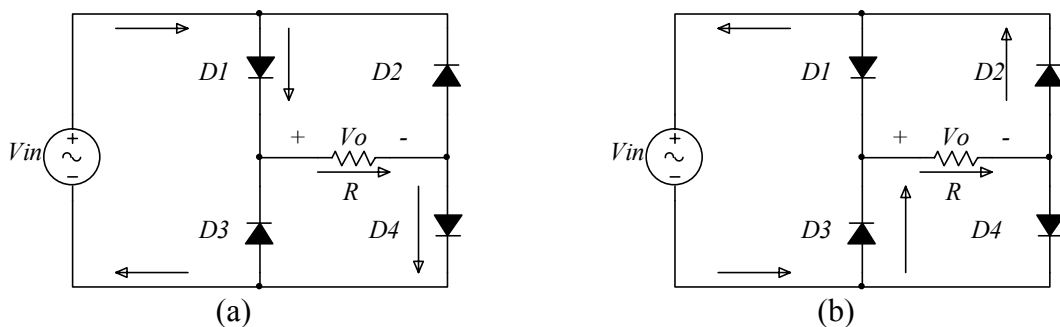
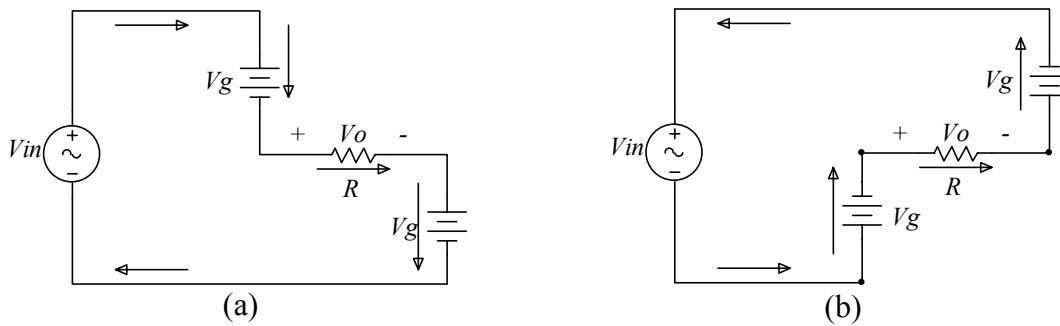


Figure 21. Direction of current in the full wave rectifier during the positive cycle if  $V_{in}$  (a) and during the negative cycle of  $V_{in}$  (b)

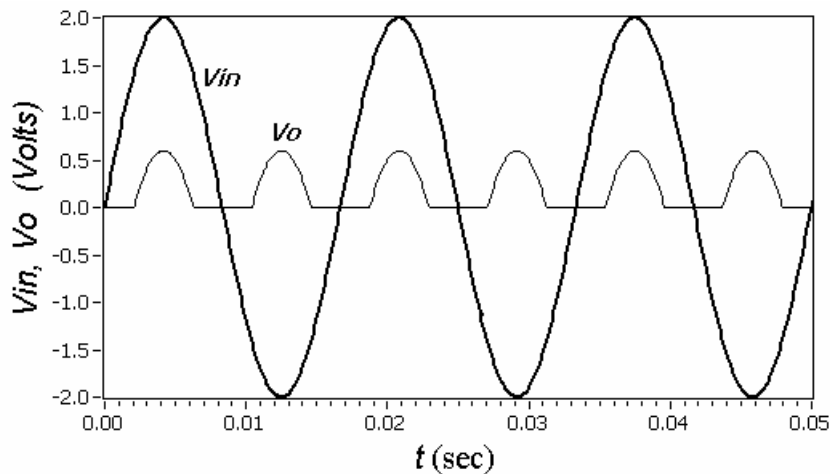
The difference in the response becomes apparent by considering the circuit equivalent of the offset model of the diode as shown on Figure 22 for the positive and negative portions of the input signal  $V_{in}$ . From KVL we see that

$$V_o = V_{in} - 2V_g \quad (1.3)$$



**Figure 22. Equivalent model of the full wave rectifier during the positive (a) and negative (b) portions of the cycle.**

The resulting output is rectified during the positive and the negative cycle of the signal  $V_{in}$  and it has the form shown on Figure 23 for a silicon diode characterized by  $V_g=0.7$  Volts. For  $V_{in}$  that have a small amplitude (not much greater than the offset voltage  $V_g$ ) the rectified signal may only be a small fraction of the input signal. Later in the term we will improve this circuit by designing a “superdiode” which will have  $V_g=0$  and thus the rectified signal will resemble the one obtained by the ideal diode model (Figure 20).



**Figure 23. Input and output signals for the full wave rectifier.**

### Obtaining the operating point.

Referring to Figure 24, the current  $I_d$ , when  $V_{in} \geq V_g$ , is

$$I_d = \frac{V_{in} - V_d}{R} \quad (1.4)$$

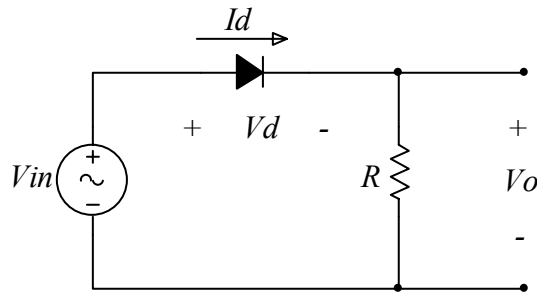


Figure 24.

This is the load line equation for this circuit. The intersection of the load line and the  $I$ - $V$  characteristic curve  $I_d = I_s(e^{v_d/v_t} - 1)$  for the device is the operating point for the diode.

This operating point is also called the quiescent point or Q-point and it gives the value of the current through the diode and the voltage across the diode.

For  $R = 100 \Omega$ , and  $V_{in} = 2V$ , the load line and resulting operating point is shown on Figure 25.

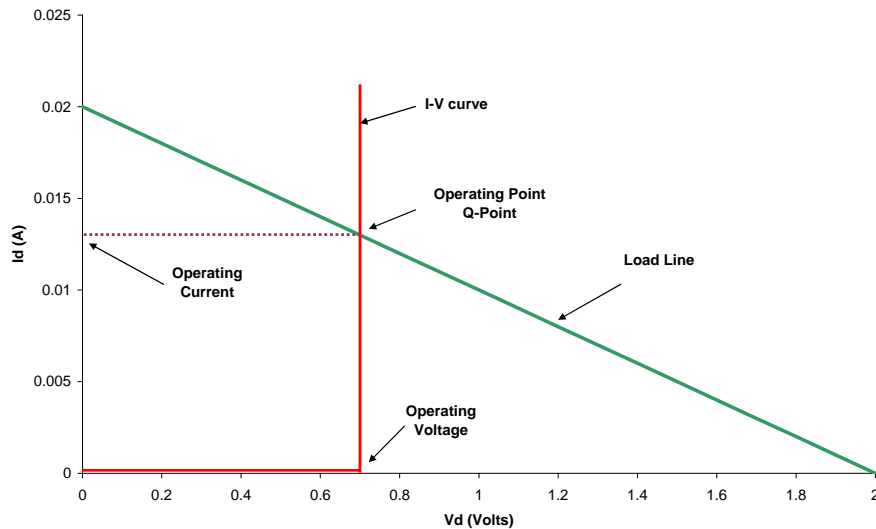
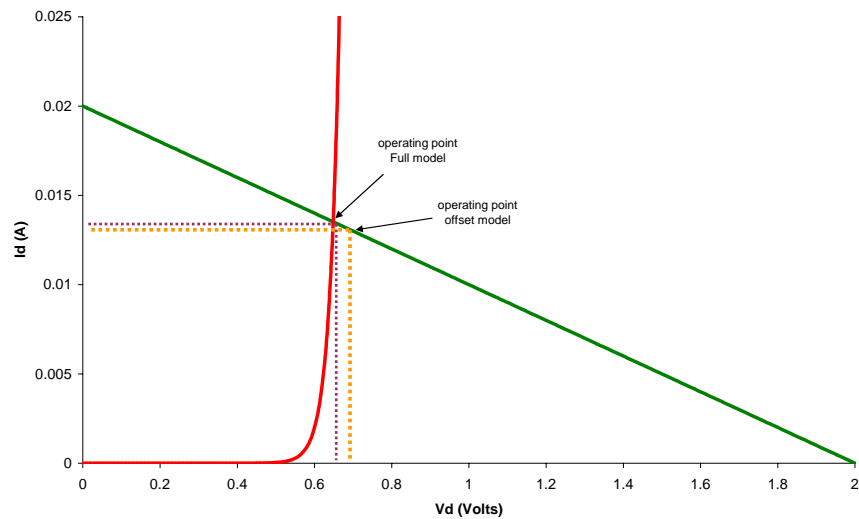


Figure 25. Load line and operating point of diode in a rectifying circuit.

For comparison let's calculate the operating point of the same circuit by using the full  $I$ - $V$  model of the diode. The load line equation is still the same but the  $I$ - $V$  characteristic will now result in a slightly different operating point. Figure 26 shows the graphical solution.

Note the small difference in the solution for the diode current for the two models. This small difference is usually ignored. However, in certain cases where the range of operating conditions is very wide the error associated with the use of the offset model may not be acceptable. Therefore, care should be taken when circuit analysis is performed with simplified models. For our scope the use of the offset model is sufficient and will be used unless stated otherwise.



**Figure 26. Load line and operating point of diode in a rectifying circuit (full diode model).**



## Reverse Bias Operation. Zener Diode

Operation of the diode in the reverse bias region is limited by the maximum allowable reverse bias voltage. As the reverse bias voltage increases above a certain value the diode breaks down and the current in the reverse bias direction increases rapidly as it is graphically demonstrated on Figure 7. The voltage at which this phenomenon occurs is called the reverse breakdown voltage. For diodes designed to operate in the forward bias region the application of a reverse bias voltage should be avoided.

However, reverse breakdown may also be a very useful phenomenon and special diodes, called **Zener** diodes, are fabricated to exhibit and exploit this property at well defined voltages. These voltages range from a few Volts to hundreds of Volts. The symbol for the Zener diode is shown on Figure 27.

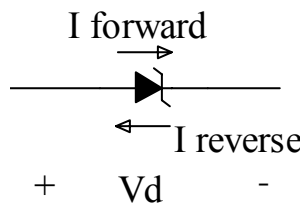


Figure 27. Symbol of Zener diode.

These diodes are very useful in providing a well defined reference voltage. Operation of these devices, like any other device, is limited by the practical considerations such as power dissipation. Let's consider an example of a voltage regulator circuit using a Zener diode. The circuit is shown on Figure 28.

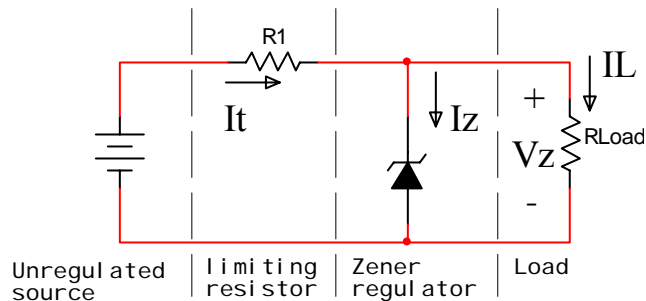


Figure 28. Zener voltage regulating circuit

As long as the Zener diode is in the reverse breakdown region, the voltage across the load is  $V_Z$ , the breakdown voltage for the diode. The current through the load  $R_L$  is then

$$I_L = \frac{V_Z}{R_L}$$

For the voltage  $V_Z$  to be regulated the current  $I_L$  must be constant. From KCL we have the constraint

$$I_t = I_L + I_Z$$

Any excess current is returned via the diode keeping the diode voltage  $V_Z$  constant.

In practical situations power considerations must be incorporated in the analysis in order to calculate and design for the maximum current that can flow through the device. We will examine this problem in a homework exercise.