Diode Circuits

Operating in the Reverse Breakdown region. (Zener Diode)

In may applications, operation in the reverse breakdown region is highly desirable. The reverse breakdown voltage is relatively insensitive to the current flowing thought the diode (the reverse current). Zener diodes are designed to operate in the reverse breakdown region and circuits containing them provide voltage regulation or voltage referencing.

The circuit shown on Figure 1(a) will be used to explore the characteristics of operation in the breakdown region. The *i-v* characteristic curve of the diode is shown on Figure 1(b). V_z is the reverse breakdown voltage and V_g is the forward voltage drop across the diode. We will focus our analysis in the reverse bias region of the *i-v* curve.
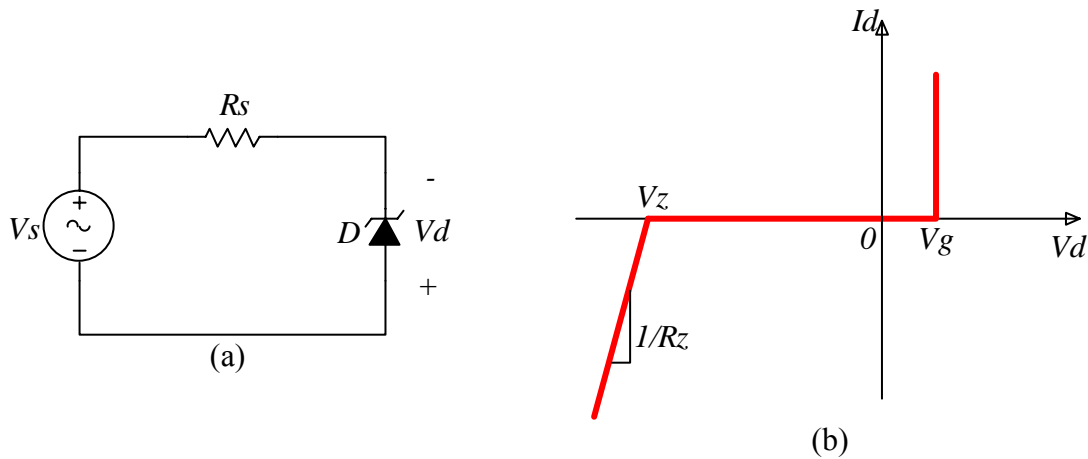

Figure 1

For the Zener diode we are using a model with a breakdown voltage V_z and an effective resistance R_z in the breakdown as shown on Figure 2 and illustrated on Figure 1.
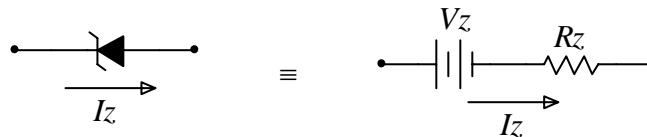

Figure 2. Zener diode model in the breakdown region

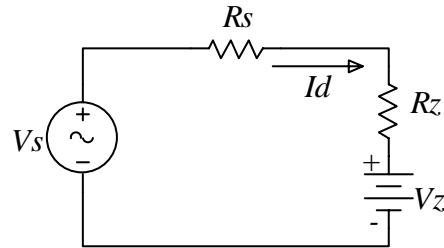With this model for the Zener diode the circuit in the breakdown region is shown on Figure 3.

Figure 3

By applying KVL to the circuit we have

$$Vz + (R + Rz)\, Id = Vs \tag{1.1}$$

Equation (1.1) is also called the load line equation and for operation in the reverse breakdown region the load line expression becomes

$$Id = -\frac{Vz}{R + Rz} + \frac{Vs}{R + Rz} \tag{1.2}$$

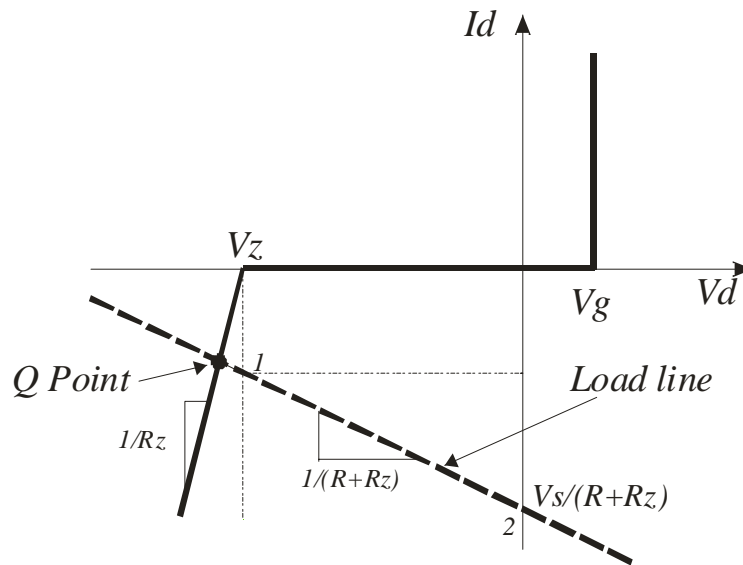The two points labeled 1 and 2 as shown on Figure 4 define the load line in the *i-v* operating space.

Figure 4

The operating point or Q point[1] is defined by the intersection of the load line equation and the *i-v* curve of the diode

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[1] Q stands for Quiescent which we will discuss in detail when we investigate transistor amplifiers.

Now let's consider the half wave rectifier circuit examined previously with the addition of a capacitor in parallel with the load resistor as shown on Figure 5.
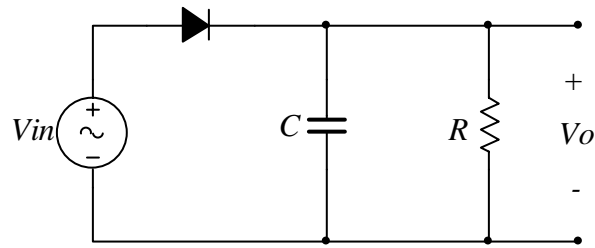

Figure 5

Initially the capacitor is uncharged (*Vo=0* Volts). The signal *Vin* is a sinusoid with amplitude *Vs* and period *T*. The silicon diode has a forward voltage drop of about 0.7 Volts. Therefore the signal *Vo* will remain at 0 Volts until the voltage *Vin* exceeds 0.7 Volts as shown on Figure 6. Once *Vin* becomes greater than 0.7 Volts the diode turns on and the voltage across the capacitor increases until *Vin* reaches its maximum value *Vs*. When *Vin* starts decreasing ($t > T_1$) the diode becomes reverse biased and the capacitor begins to discharge through the resistor R at a rate proportional to $e^{-t/RC}$.
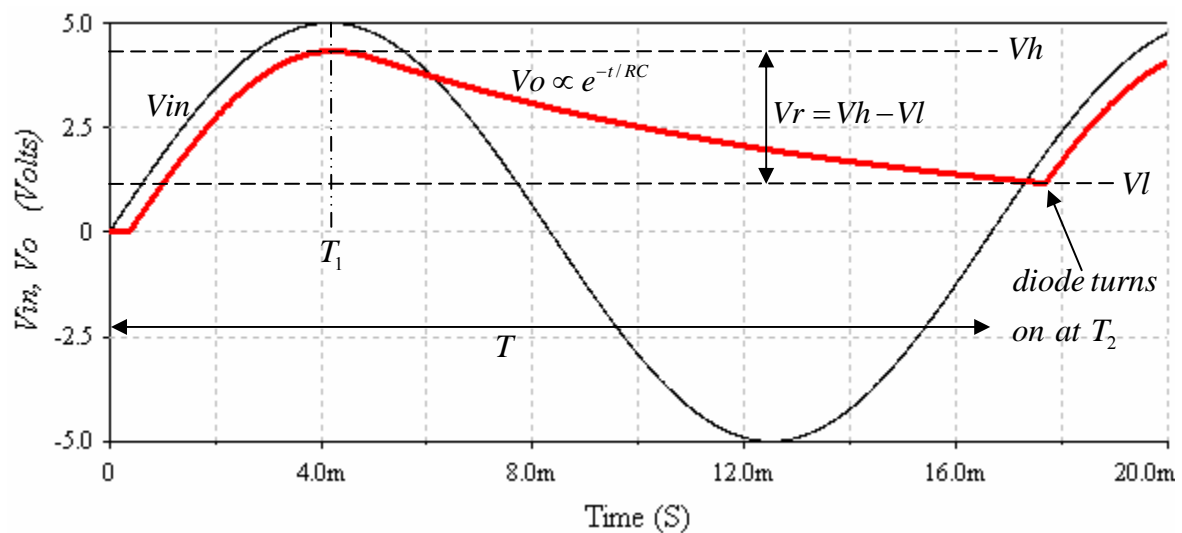

Figure 6

The voltage *Vo* for $t > T_1$ is given by

$$Vo(t) = Vh\, e^{-(t-T_1)/RC}$$ (1.3)

The voltage *Vo* continuous to decrease until the voltage drop across the diode becomes greater than 0.7 Volts. On Figure 6 this occurs at $t = T_2$ and the value of Vo at that time is

$$Vl = Vh \, e^{-(T_2 - T_1)/RC} \tag{1.4}$$

The difference between the maximum and the minimum value of *Vo*, *Vh* and *Vl* respectively, is called the ripple of the signal and it is given by

$$\begin{aligned} Vr &= Vh - Vl \\ &= Vh\left(1 - e^{-(T_2 - T_1)/RC}\right) \end{aligned} \tag{1.5}$$

In practical situations we usually would like to have a time constant *RC* large compared to $T_2 - T_1$ or equivalently to the period of the input signal *Vin*. Therefore, for $RC \gg T_2 - T_1$ the Taylor expansion of Equation (1.5) gives

$$Vr \simeq Vh \frac{T_2 - T_1}{RC} \tag{1.6}$$

At this point we see that the time $T_2 - T_1$ depends on *RC* and thus Equation (1.6) cannot be solved very easily. However, if we assume that $T_2 - T_1$ is equal to the period of the input signal (which constraints our treatment to small values of the ripple) equation (1.6) becomes

$$Vr \simeq Vh \frac{T}{RC} \tag{1.7}$$

In terms of the signal frequency the expression for the ripple for this half wave rectifier circuit becomes

$$Vr \simeq \frac{Vh}{f \, RC} \simeq \frac{Vs - 0.7}{f \, RC} \tag{1.8}$$

It is now easy by extension to see that for a full wave rectifier arrangement the ripple scales as

$$Vr \simeq \frac{Vh}{2f \, RC} \simeq \frac{Vs - 0.7}{2f \, RC} \tag{1.9}$$

Equations (1.8) and (1.9) show us that the ripple for a full wave rectifier is half of the ripple due to a half wave rectifier, resulting in a more efficient AC to DC converter.

As an extension of this analysis the plots shown on Figure 7 present the complete solution for various values to the time constant *RC*.
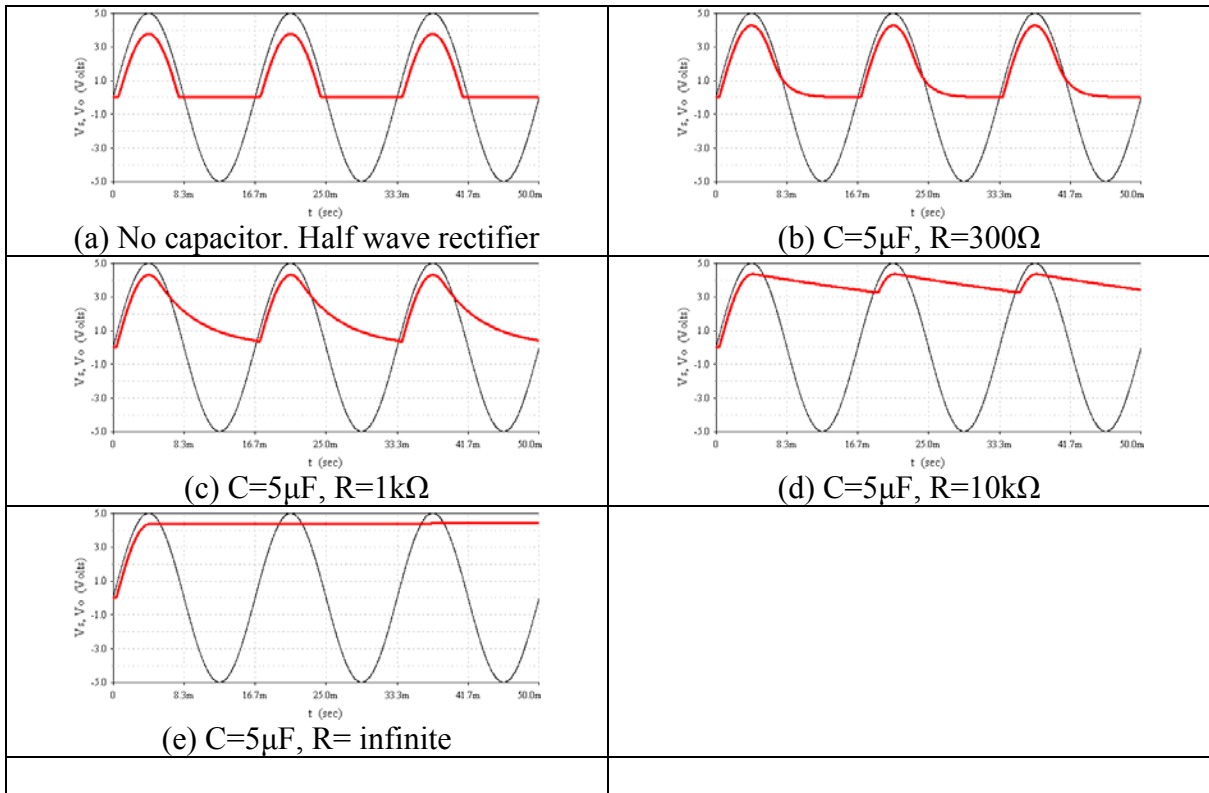
(a) No capacitor. Half wave rectifier	(b) C=5µF, R=300Ω
(c) C=5µF, R=1kΩ	(d) C=5µF, R=10kΩ
(e) C=5µF, R= infinite	

Figure 7

Light Emitting Diodes (LED)

LEDs are *pn* junction diodes that emit light at various frequencies. The light could be visible or infrared. The LED is active when it is forward biased. The i-v characteristics of an LED diode are similar to that of a regular diode except that the forward voltage may vary from 0.5 Volts to 2.5Volts depending on the type of semiconductor used.

The current that flows through the diode controls the intensity of the emitted light. When using such a diode provisions have to be taken for its protection from excessive current through it. The protection is accomplished by using a current limiting resistor as shown on Figure 8. The value of the current limiting resistor is determined by the forward voltage drop of the diode, *Vg*, the maximum current through it, *Im*, and the source voltage *Vs*. The relationship is obtained by applying KVL and it is

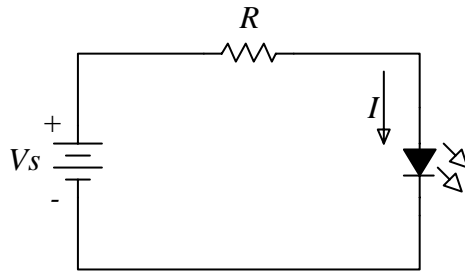$$R = \frac{Vs - Vg}{Im} \tag{1.10}$$

Figure 8. LED diode circuit.

By using an LED and a Zener diode we can create a circuit which gives turns on the LED when a voltage exceeds a certain value. Consider the circuit shown on Figure 9. The LED will turn on when the voltage Vs becomes greater than $Vz + Vg$
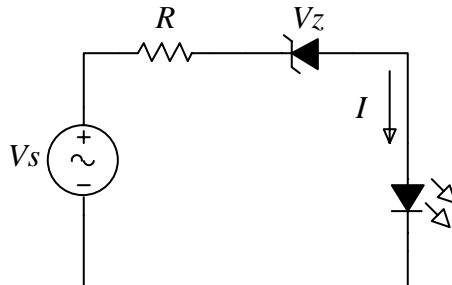

Figure 9. voltage level indication circuit

Photodiodes

When the *pn* junction of a diode is exposed to light of sufficiently high frequency the energy of the photons causes the electrons to move, thereby creating electron-hole pairs. The motion of these pairs results in a current through the diode. The symbol, for the photodiode is
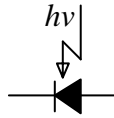

Figure 10. Photodiode symbol

Consider the circuit on Figure 11 where the photodiode is reverse biased. When the light intensity is zero, the current that flows through he diode is the reverse –saturation current which is typically very low. When the energy of the light increases, electrons are separated and there is a current flowing in the reverse bias direction. The output voltage *Vo* is proportional to the current *Ip*
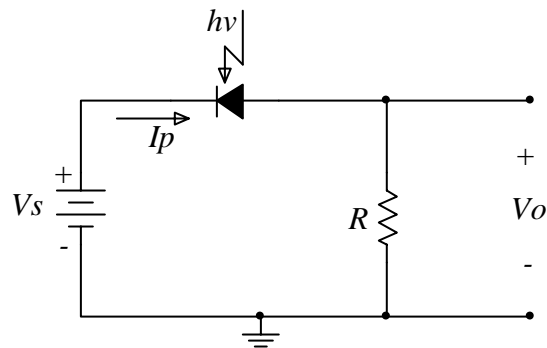
$$Vo = Ip\,R \qquad (1.11)$$

Figure 11. Photodiode circuit

Schottky Diodes

When a diode with a low forward voltage drop is required the Schottky diode may be used. The Schottky diode turns on at about 0.2 Volts compared to 0.7 Volts for the Si diode and it is characterized by a very fast switching times. The symbol, for the Schottky diode is
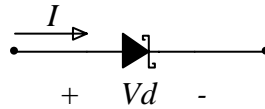

Figure 12. Symbol of Schottky diode

The fabrication process of the Schottky diode is different that that of the standard *pn* junction Si diode. The Schottky diode has a metallic layer in the place of the *p* region.

Problem:
Voltage Doubler Circuit

By replacing two diodes of the full wave rectifier with capacitors the resulting circuit is shown on Figure 13.
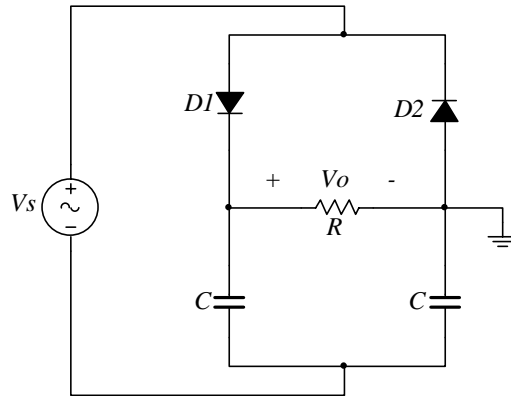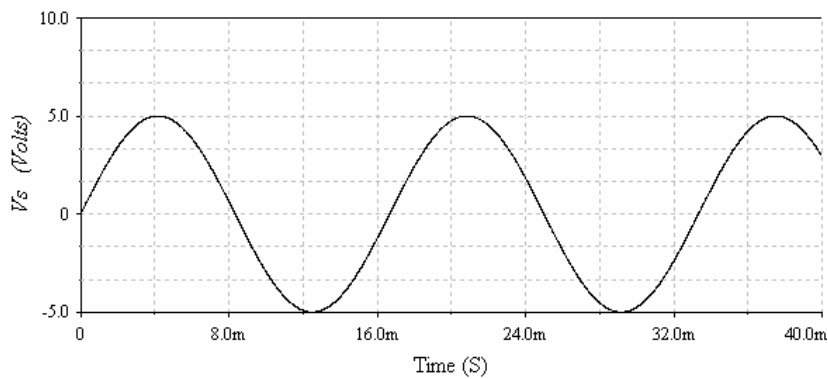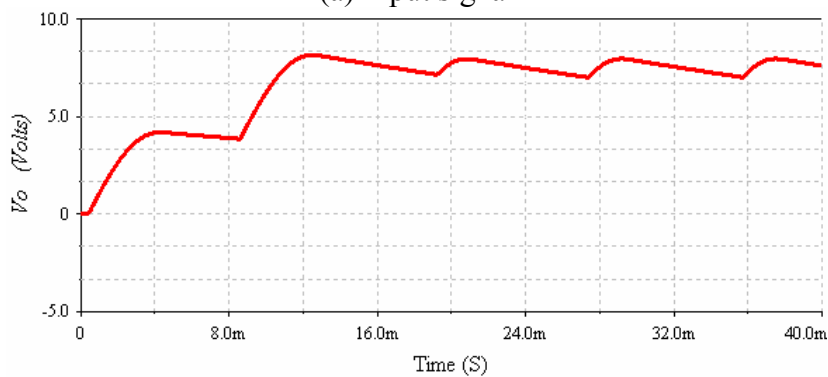

Figure 13. Voltage doubler circuit

The source signal Vs is a sinusoid with amplitude 5 Volts as shown on Figure 14. Can you explain its operation? (Look at the positive and the negative portions of Vs.)

(a) Input signal

(b) Output signal

Figure 14. Input and output of voltage doubler circuit