Lab 10: Diodes in Rectifier Circuits

1. Objectives

Understand the transient response of semiconductor pn-junction and Schottky diodes.

Study half-wave and full-wave rectifier circuits based on semiconductor diodes.

2. Introduction

Diodes under pulsed operation

It is important to understand behavior of semiconductor diodes in large signal switching mode where the diode turns rapidly from the conducting state to the non-conducting state. This happens when diodes are used in power, digital logic, pulse shaping circuits, etc. Switch-on time (establishing forward bias voltage and current across the diode) is fast comparing to switch-off time (removal of the forward bias voltage and establishing zero current). For the pn-junction diode to go from forward bias to reverse-bias state the injected minority carriers (holes in n-region and electrons in p-region) has to be removed and this process takes time.

Consider the circuit in Figure 1 with square wave $V1(t)$ applied to series connection of the diode and current limiting resistor.

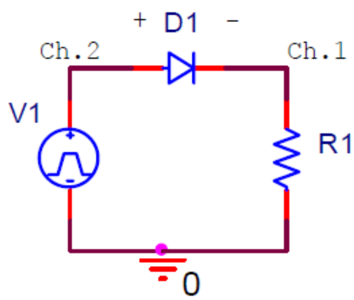

Figure 1

When $V1$ is in positive half cycle (and larger than diode turn-on voltage) the diode is forward biased. The current through the diode under forward bias (in steady state) is:

$$I_D = I_S \cdot \left(\exp\left(\frac{V_D}{n \cdot V_{th}} \right) - 1 \right) \approx \frac{|V1| - V_D}{R1}, \qquad (1)$$

where n is nonideality factor and $V_{th} \cong 0.026$ V is the thermal voltage at room temperature.

Immediately after $V1$ changes sign the voltage across the diode remains forward bias voltage ($V_D \sim 0.7$ V for Si-based pn-junction diodes) since minority carriers cannot be removed instantly (good analogy is the charge on capacitor plates). The current through the diode then is:

$$I_1 = \frac{-|V1| - V_D}{R1}. \qquad (2)$$

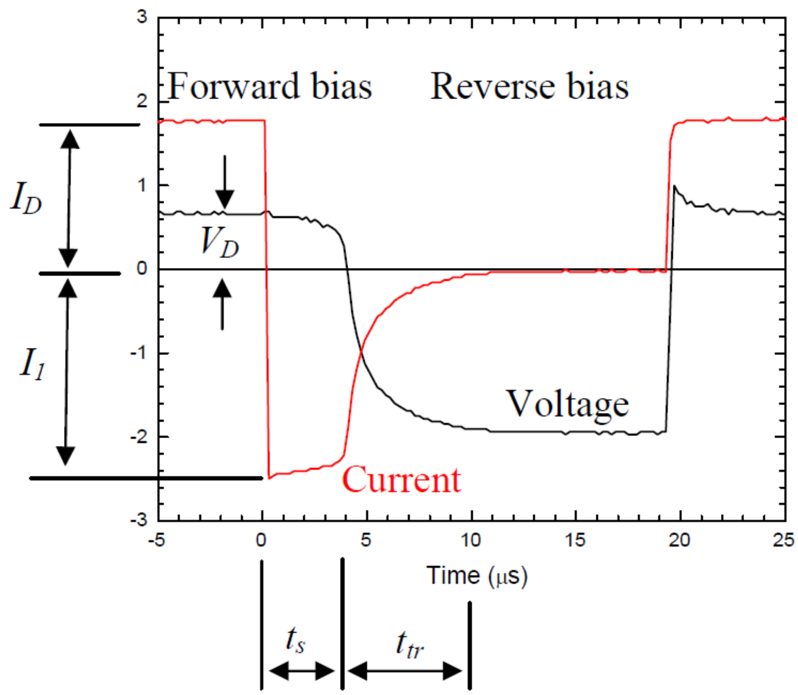

Figure 2

Figure 2 plots the temporal waveform of the current through the diode (proportional to the voltage across R1) and the voltage across it (scales are different). Note: current I_1 is larger the I_D because magnitude of the voltage applied to R1 when $V1$ changes polarity from positive to negative increases by two V_D.
The diode current waveform (Figure 2) can be obtained by measuring voltage across R_1 (Oscilloscope Channel 1 in Figure 1). The diode voltage waveform can be obtained difference between Channel 2 and 1 signals.

During period of time $t_{S,}$ known as the *storage time*, the excess minority carrier charge Q is being removed. During that time the diode remains essentially forward biased.

$$t_S \approx \frac{Q}{I_1} \tag{3}$$

Once the minority charge has been removed, the diode reverse biases in a time controlled by the product of circuit resistance $R1$ (Figure 1) and average depletion capacitance C_j of the diode junction. This time is known as the *transition time* t_{tr}

$$t_{tr} \sim 3 \cdot R1 \cdot C_j \tag{4}$$

The diode *recovery time* is a sum of these two parameters:

$$t_{rec} = t_s + t_{tr} \tag{5}$$

In general, the diode recovery time depends on the diode design and operating conditions as well. For instance, Schottky diodes have shorter recovery time since they are free from minority carrier charge accumulation.

Half-wave and full-wave rectifier circuit

The circuit in Figure 3 is known as a half-wave rectifier. Often rectifiers are used to obtain DC output from periodic AC input (such as sine or square wave). Capacitor is used to maintain the voltage across load R1 when the diode is switched off. The capacitor is connected in parallel to the load (C1 in Figure 3).

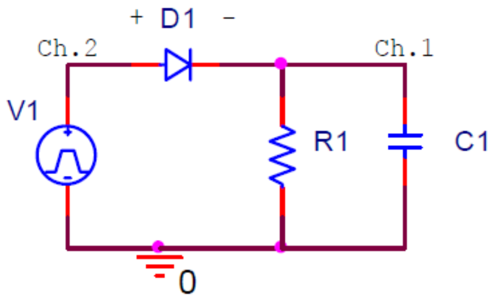

Figure 3

For positive input half-wave, the load voltage (across R1 and, hence, also across C1) is equal to the input value V1 minus the voltage drop across the diode under forward bias (i.e. ~0.7 V for Si-based pn-junction diodes). The capacitor C1 is being charged quickly because the time constant for charging process is small due to small series resistance of the diodes. For negative input half-wave, the diode is off and the output waveform is defined by discharging process with time constant R1*C1. This time constant is selected large compared to the period of input signal to maintain the output voltage until the next turn-on diode cycle. Thus, for the circuit in Figure 3, the DC output voltage can be close to the amplitude of the input AC signal.

The circuit in Figure 3 works satisfactory when the load resistance is sufficiently high. In the opposite case the required capacitance value becomes impractical. Also, the negative half cycle of the input signal waveform is wasted.

With the help of a full-wave rectifier shown in Figure 4, the energy transfer from source V2 to load R1 is performed for both positive and negative input half-waves.

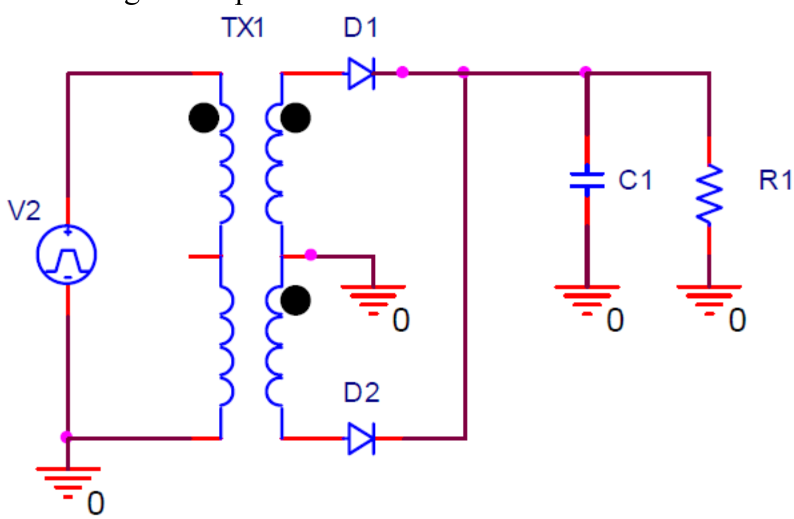

Figure 4

The voltage source seen from the transformer secondary has floating ground. Grounding one or another end of the secondary changes the reference direction of such a source, and, correspondingly, turns by 180^0 its phase with respect to the signal generator voltage V2. Grounding the secondary central tap creates two out-of-phase voltages simultaneously. When the input half-wave is positive, the top end of the secondary is positive and the bottom end is negative with respect to the tap. Consequently, diode D1 will be on while diode D2 is off. When the input half-wave is negative, diodes D1 will be off and D2 will be on. Thus, the energy is being transferred to the load during both half-waves of the input voltage and the time constant R1*C1 can reduced twice. Indeed, the rectifier circuit shown in Figure 3 is very popular.

3. Preliminary lab

For rectifier diode (1N4002), simulate in PSPICE:

<u>For the circuit in Figure 1:</u> obtain the timing diagrams for voltage across and current through the diode (on a separate plot) for the square wave input voltage changing from - 10V to +10 V. Select the resistor values in Ohm as the last three nonzero digits of your ID number. Select the sufficient time range for simulation to observe the diode recovery process (10 μs is a good starting point). Determine the diode recovery time.

<u>For the circuit in Figure 3:</u> study the effects of filter capacitance and load resistance on the output waveform. Input voltage is ±10 V square wave with 10 kHz frequency. On the timing diagrams plot the output voltage (across R1) for two values of capacitor C1: 0.1 μF, 1 μF; and for two values of resistor R1: 1 kΩ, 100 Ω (4 traces total). Comment on the observed tendencies.

4. Experiment

The experiments will be performed with a rectifier diode (**1N4002**) and a Schottky diode (**1N5819**).

<u>*Transient response*</u>
Observe the diode recovery characteristics using circuit in Figure 1. Apply a square wave with the amplitude of 10 V and the frequency of 10 kHz. Obtain the traces for the diode voltage and current and store them in the data files using the scope remote control interface. Use two values for R1: 1 kΩ and 100 Ω. Compare the recovery characteristics of pn-junction and Schottky diode.

<u>*Half-wave rectifier*</u>
Use Schottky diode in Figure 3 circuit. Input a sine wave of 2 V amplitude and 1 kHz frequency. Measure the DC component of the output voltages using DMM and the amplitude of AC voltage ripples using oscilloscope. Perform these measurements for two resistor (1 kΩ, 100Ω) and two capacitor (0.1 μF, 1 μF) values. Comment on the observed changes.

<u>*Full-wave rectifier*</u>
Assemble the circuit in Figure 4 using two rectifier diodes, a 1 kΩ resistor and a 0.1 μF capacitor. Apply a sine wave and select a proper frequency to obtain a DC like output signal. Comment on the value of the frequency you have selected (how does it compares to the discharge time constant?). Remove the capacitor; measure the output waveform and comment on the observed changes.

<u>*Report*</u>

The report should include the lab goals, short description of the work, the experimental and simulated data presented in plots, the data analysis and comparison followed by conclusions. Please follow the steps in the experimental part and clearly present all the results of measurements.