Experiment 5
Transient Responses of Diodes and Rectifiers

EECS 170A - Lab Bench #1
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1 Procedure

The objective of the experiment is to measure the minority carrier storage time of p-n junction diodes, referred to as t_s, the transient response, and to note differences in the transient response of Schottky diodes. The first part of the experiment consists of building a full-wave diode rectifier and observing the many voltage waveforms on the oscilloscope. A simple circuit is built with a waveform generator that has an internal resistance of 50Ω. The generator is connected to a rectifier p-n junction diode in series, while also having a resistor R_L in parallel with the oscilloscope. The transient response is observed from the circuit after applying a pulse waveform across the test diode. An input waveform and output waveform should be seen using the oscilloscope. The reverse bias current, forward bias current, and storage time are then measured while the minority carrier lifetime τ is observed on the side of the junction that is lightly doped. Lastly, there should be an observation of no rectifying function when the voltage waveform period becomes smaller than $2t_s$. Switch the rectifier p-n junction diode with a switching p-n junction diode and repeat the same steps. For the final circuit, replace the switching p-n junction diode with a Schottky diode and repeat the same steps. For the final part of the experiment a full-wave diode rectifier is built using 4 diodes that are connected to a function generator and a resistor (R). The parameters of the waveform generator are set to a voltage of 10Vpp with a frequency of 1kHz, and set the resistor value to 300Ω. Record the input voltage V_{in} and measure the voltage across the load resistor.

2 Results and Analysis

2.1 Transient Response of Diodes

2.2 Full-Wave Bridge Rectifier

Figure 1: Full-Wave Bridge Rectifier Circuit

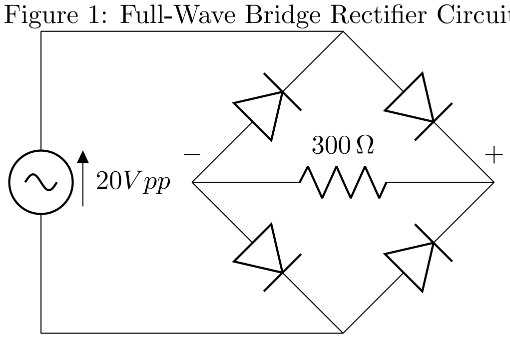


Figure (9) displays a full-wave bridge rectifier circuit. The circuit's specification requires that it take an input sinusoidal signal and produce an output voltage that is the absolute value of that signal with the least amount of error possible. The output voltage is measured over the resistor, which shall be referred to as R. In reality, this ideal is not reached. The experiment demonstrates the degree to which the specification is satisfied. The full-wave bridge rectifier circuit takes advantage of the fact that diodes essentially act as broken circuits when the applied voltage is less than its threshold voltage and act as short circuits when the applied voltage exceeds its threshold voltage. This is a simplification of the Shockley diode model:

$$I_{diode}(V_{applied}) = I_0(e^{\frac{qV_{applied}}{k_B T}} - 1) \tag{1}$$

In equation (1), I_0 is the reverse saturation current, q is the elementary charge, k_B is Boltzmann's constant, and T is temperature. A more ideal model treats the diode as the perfect switch described above, namely that the diode acts as a broken circuit unless $V_{applied}$ exceeds its threshold voltage, assumed to be about 0.7V and referred to as V_{Th}. Figure (2) below compares these two models in a graph. The graph demonstrates that this more idealized model accurately characterizes the behavior of the diode. It shall be used instead to describe the diode's characteristics.

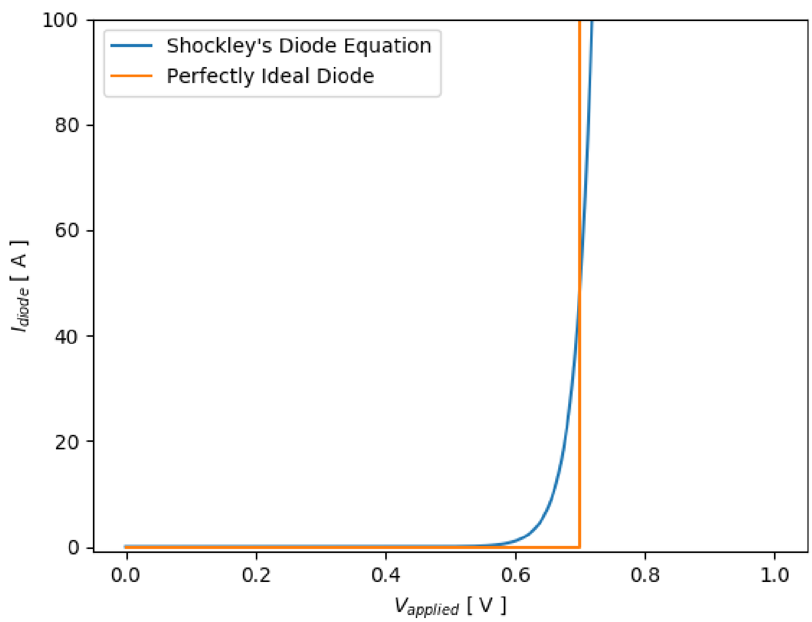


Figure 2: Shockley Diode Model vs. Perfectly Ideal Diode

I_0 is set to 0.1nA. Temperature is assumed to be 300K. Threshold voltage of perfectly ideal model is assumed to be 0.7V.

A diode is said to be enabled when the applied source voltage, which shall be called V_A, meets or exceeds its threshold voltage. Enabled diodes are drawn in green. Two cases are to be considered: when $V_A > 2V_{Th}$ and when $V_A < 2V_{Th}$. $2V_{Th}$ must be used since the voltage must enabled two diodes in series as seen in the figures below. Note that $|V_A| < 2V_{Th}$ is trivial since no voltage drops over the load resistor R.

When $V_A > 2V_{Th}$, the diodes in figure (3) are enabled. The voltage measured over the resistor is clearly positive due to the direction of positive current flow. The positive current flow direction is indicated by an arrow.

Figure 3: Full-Wave Rectifier when $V_A > 2V_{Th}$

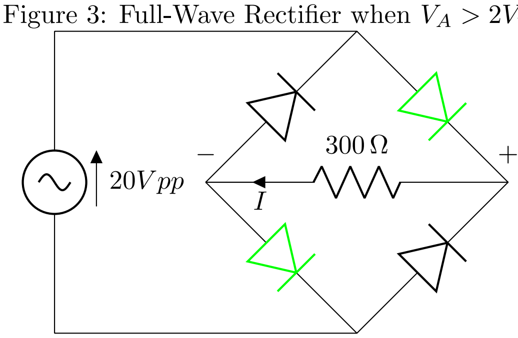
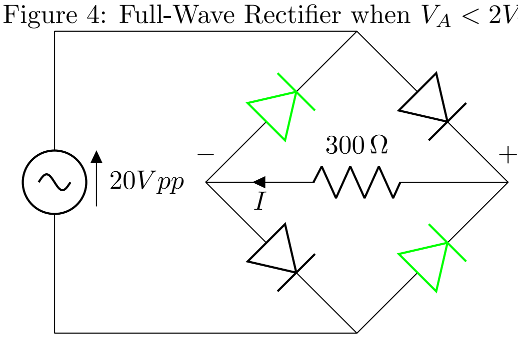


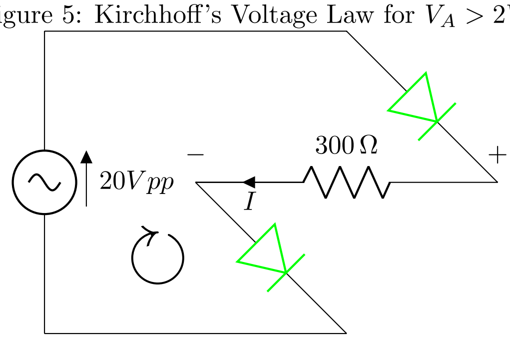
Figure (4) demonstrates the case when $V_A < 2V_{Th}$. Again, the output voltage taken over the resistor is positive due to the direction of positive current flow.

Figure 4: Full-Wave Rectifier when $V_A < 2V_{Th}$



A more quantitative description of this behavior can be obtained. In the $V_A > 2V_{Th}$ case, Kirchhoff's voltage law may be applied:

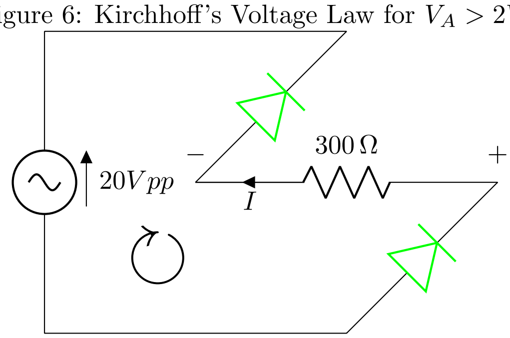
Figure 5: Kirchhoff's Voltage Law for $V_A > 2V_{Th}$



$$+V_A - V_{Th} - V_{out} - V_{Th} = 0 \rightarrow V_{out} = V_A - 2V_{Th} \tag{2}$$

The same method can be applied to the $V_A < 2V_{Th}$ case.

Figure 6: Kirchhoff's Voltage Law for $V_A > 2V_{Th}$



$$+V_A + V_{Th} + V_{out} + V_{Th} = 0 \rightarrow V_{out} = -V_A - 2V_{Th} \tag{3}$$

These behaviors can be generalized in the following result for the output voltage of the full-wave rectifier circuit in figure (9):

$$V_{out}(V_A) = max(|V_A| - 2V_{Th}, 0) \tag{4}$$

A plot of the expected output voltage against the input voltage is shown in figure (7):

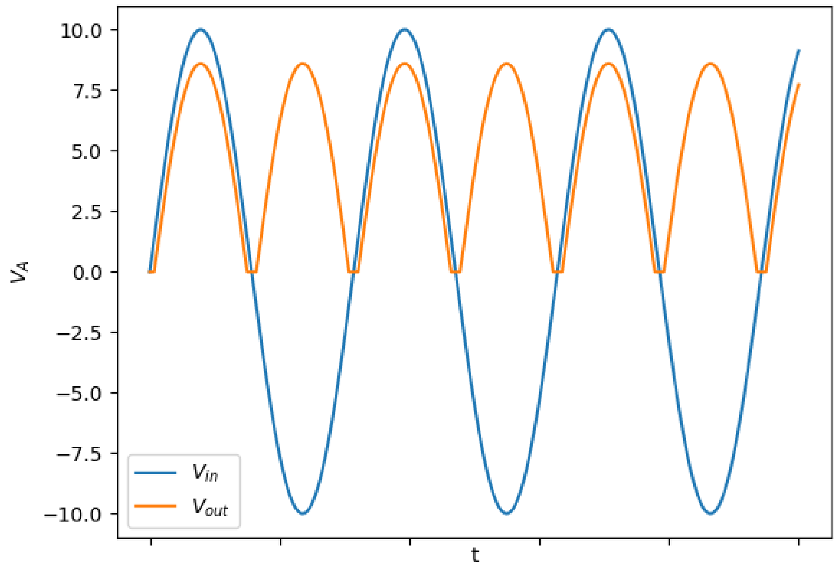


Figure 7: Full-Wave Bridge Rectifier Expected Result

The full-wave bridge rectifier is constructed using 1N4005 rectifier diodes. The measured result is presented in figure (8) below:

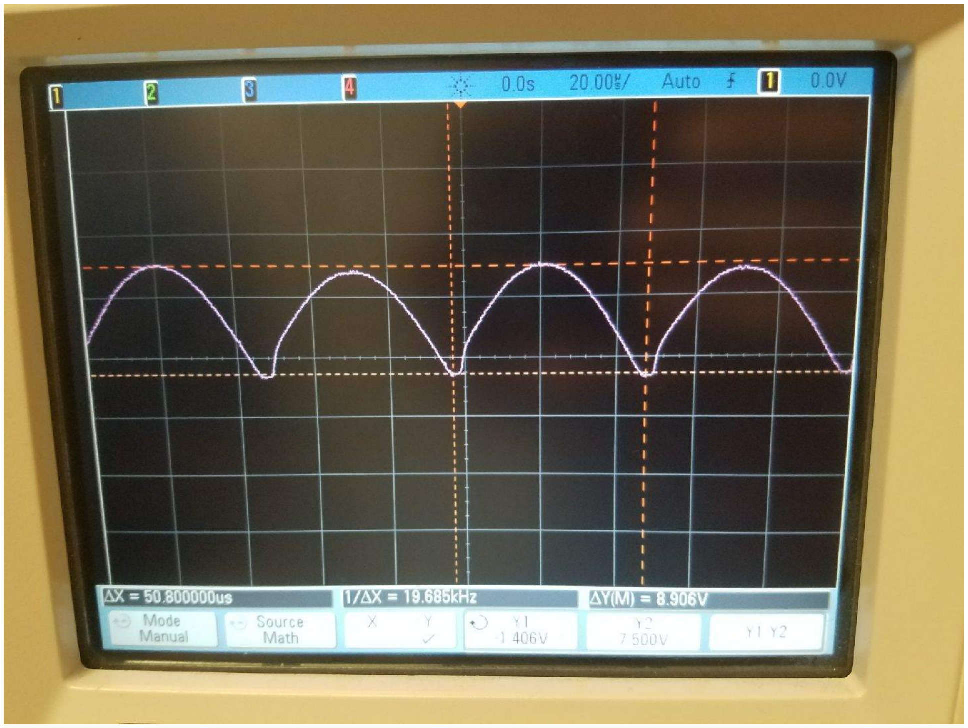
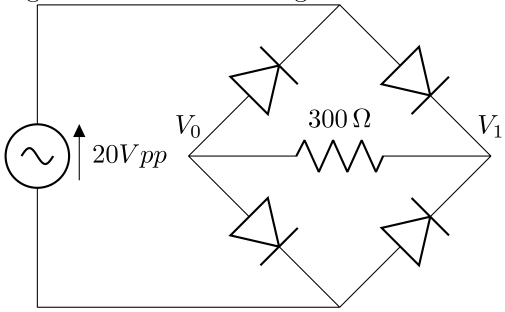


Figure 8: Measured Amplitude of Full-Wave Rectifier

The oscilloscope cannot directly measure the output voltage because the probe must be connected to ground. Thus, in figure (**??**), V_1 and V_0 are probed:

Figure 9: Full-Wave Bridge Rectifier Circuit



Without proof, $V_{out} = V_1 - V_0$. Thus, by subtracting these voltages, V_{out} can be measured. V_{out} is displayed with V_1 in yellow and V_0 in green in figure (10) below:

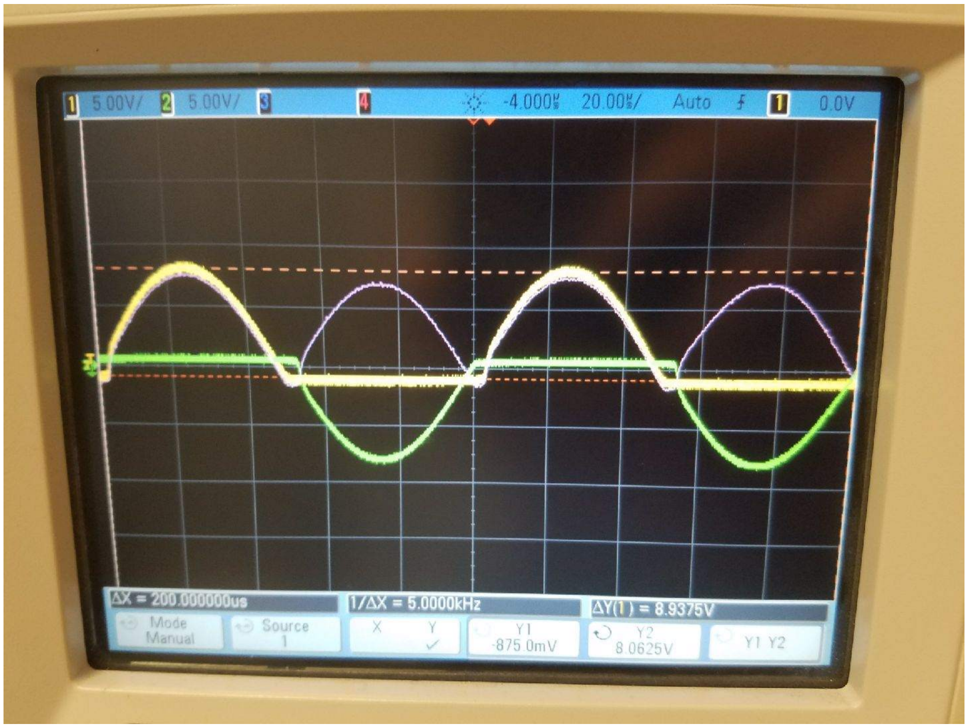


Figure 10: Measured Amplitude of Full-Wave Rectifier with Input Signals

Input voltage is 20Vpp. Frequency is 10kHz.

The input source voltage could not be captured in the same plot. This is because only two probes for the oscilloscope are available. Two are required to measure the output voltage in this manner. Thus, a third would be needed to measure the input signal.

The peak and trough voltages of V_{out} relative to the input supply voltage V_A (as determined from the reading on the power supply) are reported in table (1). Note that the absolute value of all voltages is reported:

Table 1: Peak and Trough Voltages of V_{out} and V_A

	Measured Voltage [V]	Source Voltage [V]	Difference [V]
Peak	8.906	10	1.094
Trough	8.593	10	1.407

Equation (4) predicts that the absolute value of the peak of V_{out} is below the absolute value of the peak or trough of V_A by $2V_{Th}$, assuming that $|V_A|$ at the peak and trough meets or exceeds $2V_{Th}$. Table (2) presents the results compared to theory. The full-wave bridge rectifier very closely aligns with theoretical results:

Table 2: Theoretical vs. Measured Results for Full-Wave Rectifier

	Measured Voltage [V]	Theoretical Voltage [V]	Percentage Error
Peak	8.906	8.6	3.6%
Trough	8.593	8.6	0.1%

3 Discussion

3.1 Transient Response of Diodes

3.2 Full-Wave Bridge Rectifier

The full-wave bridge rectifier results align quite well with theory. However, the peak measurement does have slightly more error than the trough measurement. These errors are a result of either an asymmetry in the source voltage or an asymmetry in the threshold voltages of the diodes. The former is not possible to prove due to the fact that the source voltage is not probed in the experiment. However, if the sinusoidal source voltage's peak is higher than the reported value on the power supply, this would explain why the measured voltage for the output voltage's peak is higher than expected. Furthermore, the diodes may differ in threshold voltage. Differences in threshold voltage are a result of either temperature, material, or doping variations:

$$V_{bi} = \frac{k_B T}{q} ln(\frac{N_A N_D}{(n_i(T))^2}) \tag{5}$$

Temperature is likely not the cause since the temperature in the room in which the experiment is conducted is essentially uniform, which would not explain the asymmetry in the measurements. A better explanation is that the doping concentrations vary slightly from diode to diode due to slight nonidealities in the manufacturing process. So, the diodes along the enabled path when the source voltage is positive could have slightly lower threshold voltages than the diodes along the other path.

4 Appendix

The following script is used to generate the theoretical full-wave recitifer plot in figure (7):

```
#!/usr/bin/python

import numpy as np
import matplotlib.pyplot as plt
```

```
V0 = 10
Vth = 0.7

t = np.linspace( 0 , 100 , 10000 )
Vin = V0 * np.sin( 0.2 * t )
Vout = np.array([])
for point in Vin:
        out_val = 0
        if abs( point ) > 2 * Vth:
                out_val = abs( point ) - ( 2 * Vth )
        Vout = np.append( Vout , [ [ out_val ] ] )
vin_plt , = plt.plot( t , Vin , label = "$V_{in}$" )
vout_plt , = plt.plot( t , Vout , label = "$V_{out}$" )
plt.tick_params( labelbottom = 'off' )
plt.xlabel( "t" )
plt.ylabel( "$V_{A}$" )
plt.legend( handles = [ vin_plt , vout_plt ] )
plt.savefig( "../images/full_wave_rect.PNG" )
```

The following script is used to generate tables (1) and (2):

```
#!/usr/bin/python

# Roman Parise
# Full-Wave Rectifier Data

# Input src: 20 Vpp

import common

TABLES_DIR = "../tables/"
FWR_DATA_FNAME = "fwr_data.csv"
FWR_ERR_FNAME = "fwr_err.csv"

# Data for peaks and troughs table

rectified_amplitude_peak = 8.906 #V
rectified_amplitude_trough = 8.593 #V

source_peak = 10 #V
source_trough = 10 #V

diff_peak = abs( source_peak - rectified_amplitude_peak )
diff_trough = abs( source_trough -
   rectified_amplitude_trough )

data_headings = [ "" , "Measured Voltage [ V ]" , "Source
```

```
    Voltage [ V ]" , "Difference [ V ]" ]
peak_data = [ rectified_amplitude_peak , source_peak ,
    diff_peak ]
trough_data = [ rectified_amplitude_trough ,
    source_trough , diff_trough ]
data_matrix = [ data_headings , [ "Peak" ] + peak_data ,
    [ "Trough" ] + trough_data ]

common.write_csv_from_matrix( TABLES_DIR + FWR_DATA_FNAME
    , data_matrix )

# Errors from theory table

threshold_voltage = 0.7 #V

th_rect_amp = lambda V : abs( V ) - ( 2 *
    threshold_voltage )
th_rect_amp_peak = th_rect_amp( source_peak )
th_rect_amp_trough = th_rect_amp( source_trough )

data_headings_err = [ "" , "Measured Voltage [ V ]" , "
    Theoretical Voltage [ V ]" , "Percentage Error" ]
peak_data_err = [ rectified_amplitude_peak ,
    th_rect_amp_peak , common.fmt_perc_err(
    rectified_amplitude_peak , th_rect_amp_peak ) ]
trough_data_err = [ rectified_amplitude_trough ,
    th_rect_amp_trough , common.fmt_perc_err(
    rectified_amplitude_trough , th_rect_amp_trough ) ]
data_matrix_err = [ data_headings_err , [ "Peak" ] +
    peak_data_err , [ "Trough" ] + trough_data_err ]

common.write_csv_from_matrix( TABLES_DIR + FWR_ERR_FNAME
    , data_matrix_err )
```

Lastly, this script is used to generate figure (2):

```
#!/usr/bin/python

# Roman Parise

import matplotlib.pyplot as plt
import numpy as np

I0 = 1e-10
Vthermal = 26e-3
infty = 1e25
```

```
Va_shock = np.linspace( 0 , 1.0 , 1000 )
shockley_diode = I0 * ( np.exp( Va_shock / Vthermal ) - 1
    )

Va_ideal = np.linspace( 0 , 0.7 , 1000 )
ideal_diode = [ 0 ] * ( len( Va_ideal ) - 1 ) + [ infty ]

plt.xlabel( "$V_{applied}$ [ V ]" )
plt.ylabel( "$I_{diode}$ [ A ]" )

plt.ylim( -1 , 100 )

shock_plt , = plt.plot( Va_shock , shockley_diode , label
   = "Shockley's Diode Equation" )
ideal_plt , = plt.plot( Va_ideal , ideal_diode , label = "
   Perfectly Ideal Diode" )
plt.legend( handles = [ shock_plt , ideal_plt ] )
plt.savefig( "../images/ideal_diode.PNG" )
```