Laboratory 3 (2 days):
Diode characteristics, Small-signal models, Diode circuits

Overall notes:

- This laboratory has ***two sessions*** allocated for completion.
  - 1st day: Pre-Lab Exercise 1, Exercise 1, and optionally Exercise 2
  - 2nd day: Pre-Lab Exercise 2, Exercise 3, and optionally Exercise 4
- You will not be able to use the benchtop oscilloscope for some parts of this laboratory. Remember to bring your Discovery Board
- Differential measurements are needed across a component when neither nodes are ground. The Discovery Board always makes differential measurements, though, you need to use both the solid and the striped probe lines. The benchtop oscilloscope does not have a differential input option.

Reminder from previous laboratory

- You should include screenshots or image snapshots of your results in the report. Oscilloscope plots should include both the input and the output waveforms.
- Screenshots of waveforms can be obtained using Mobile Studio or Discovery Board. If you use the benchtop equipment instead, capture an image using your phone and include it in your report.

Material covered:

- I-V characteristics for standard diodes
- Small signal models for standard diodes
- Rectifier circuits
- I-V characteristics for Zener diodes
- Small signal models for Zener diodes

Data Acquisition:

- Discovery Board:
  - Raw data can be obtained using the Export tab in the upper left corner. The default option should be 'csv', which is a file type that can be imported into Excel or Matlab.

Adding a PSpice library:

1. Download "diode.olb"
2. You need to put the "diode.olb" file in a directory that looks like the following

   C:Orcad/Orcad_16.3_Demo/tools/capture/library/pspice

   The version path name may be slightly different, but everything after /tools should be the same
3. Download "diode.lib"
4. You need to put the "diode.lib" file in a directory that looks like the following

C:Orcad/Orcad_16.3_Demo/tools/pspice/library

The version path name may be slightly different, but everything after /tools should be the same

5. Navigate to the following directory

   C:Orcad/Orcad_16.3_Demo/tools/pspice/library

6. Edit the nomd.lib file using notepad (or any text editor)
7. Add the following line

   .lib "diode.lib"   ;diode lib added

8. In PSpice, open the Place tab and click on Part
9. Under the Place Part, select Add Library and add the diode.olb file
10. You should now see a new collection of Diode models

Using the PSpice to make diode *I-V* plots

1. Run the transient simulation
2. In the simulation result window, open the Plot drop down list and choose Axis Settings.
3. Select the Axis Variable button and select V(D1:1).
4. Select OK and close the window
5. Open the Trace drop down list and choose I(D1)
6. Select OK and close the window.

LTSpice

1. Please note that the use of LTSpice is also acceptable

Using the Discovery Board to make *I-V* plots

1. To the lower right of the RUN button, select Add Channel
2. Choose Add Mathematic Channel and pick Custom
3. On the Custom page, implement your desired equation. For example, to obtain a current plot for the Channel 1 voltage input, bring up the chosen Channel 1 and divide by the resistance value.
4. You will now have a math plot.
5. Select the Add XY button, the third option on the second row of icons at the top.
6. A new window will open, in the upper left of that window, click on the Options button.
7. You can now pick your *x* and *y* axis to create *I-V* (or other types) of plots.

Pre-Lab Exercise 1

1. In Spice, implement the diode circuit shown below (Figure1). Use the diode component D1N4004 or any other generic diode. Set the source voltage to a 100 Hz sinusoidal wave with a 2 V amplitude.

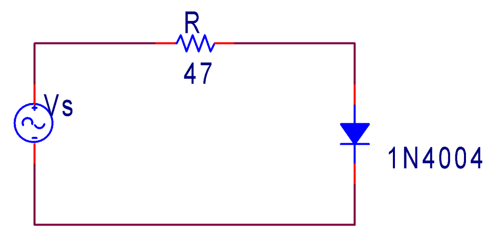

Figure 1: Diode circuit

Plot the V-I characteristics of the diode. You should see a curve similar to the exponential curve we drew in class.

Estimate the turn-on voltage of the diode.

2. In Spice, implement the diode circuit shown below (Figure 2). The circuit includes a DC source and an AC source. Set the DC voltage to 0.8 V. Set the AC sinusoidal voltage to 30 mV peak-to-peak with frequency 100 Hz.

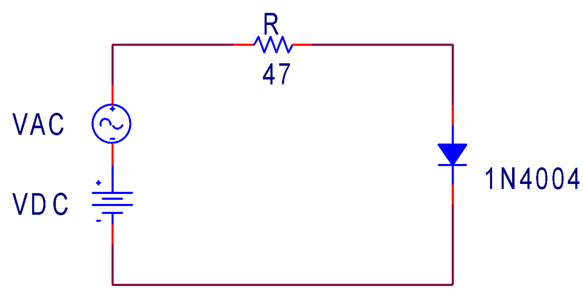

Figure 2: Diode circuit

Measure the peak-to-peak AC voltage (V_{AC}) across the diode, and the peak-to-peak AC current (I_{AC}) through the diode.

Determine the **simulated** differential diode resistance r_D ($r_D = V_{AC} / I_{AC}$). Then determine the **theoretical** differential diode resistance r_D ($r_D = V_{thermal} / I_{DC}$) at a DC bias of 0.8 V (recall $V_{thermal}$ = 26 mV). Do simulation and theory agree?

3. Set the DC voltage to 1.5 V. Measure the peak-to-peak AC voltage (V_{AC}) across the diode, and the peak-to-peak AC current (I_{AC}) through the diode. (Results may be a bit noisy.)

Determine the **simulated** differential diode resistance r_D ($r_D = V_{AC} / I_{AC}$). Then determine the **theoretical** differential diode resistance r_D ($r_D = V_{thermal} / I_{DC}$) at a DC bias of 1.5 V (recall $V_{thermal}$ = 26 mV). Do simulation and theory agree?

Pre-Lab Exercise 2

1. In Spice, implement one of the Exercise 2 diode circuits (Figure 3, shown below). Set the source voltage to a 250 Hz, 4 Vpp sinusoidal signal. Recall: $P = V_{RMS} \times I_{RMS} = I_{RMS}^2 \times R = V_{RMS}^2 / R$. Also recall, for a sinusoidal wave: $V_{RMS} = V_{Amplitude} / 2^{1/2}$

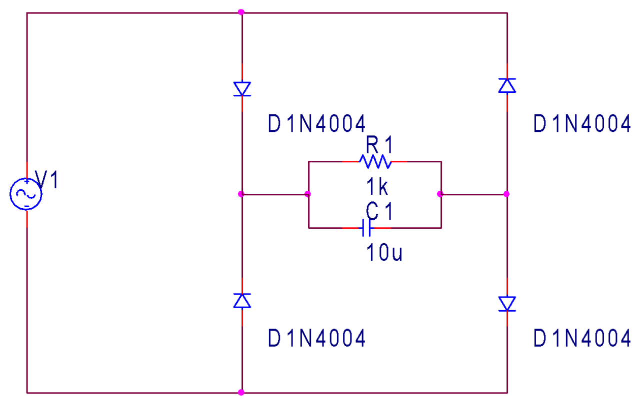

Figure 3: Diode rectifier bridge circuit

Use current probes to plot the current (versus time) at the source, and at the load.

Estimate the average power provided by the source, and the average power consumed by the load.

How efficient is the power conversion (*i.e.*, output power / input power) of the full wave rectifier?

2. Implement in Spice the half-wave rectifier circuit shown below (Figure 4). Use a source voltage V_1 with $V_{Offset} = 0$ V, $V_{Amplitude} = 8$ V, and $f = 250$ Hz.

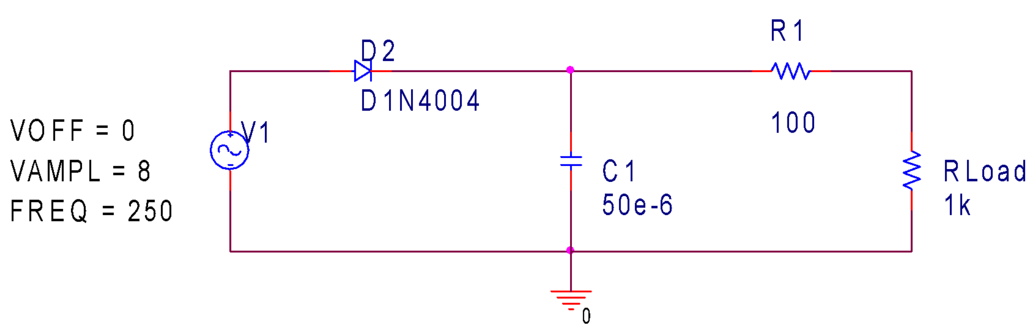

Figure 4: Diode circuit

Plot the load voltage versus time.

Estimate the average load voltage and the ripple voltage.

3. Add a Zener diode (part number D1N751) in parallel with the load as shown below. Use a source voltage V_1 with V_{Offset} = 0 V, $V_{Amplitude}$ = 8 V, and f = 250 Hz.

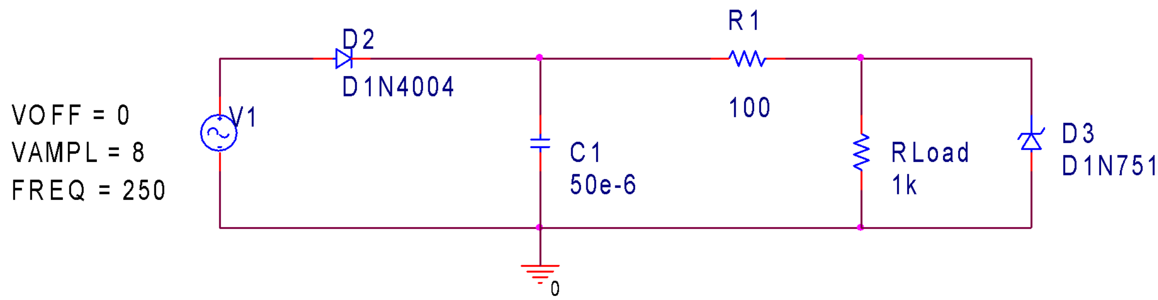

Figure 5: Diode circuit

Plot the load voltage versus time. Estimate the average load voltage and the ripple voltage.

What effect does the regulator (Zener diode) have on the average load voltage? And on the ripple voltage?

Exercise 1: Diode characteristics

1. Using the 1N4004 Diodes, build the circuit shown below (Figure 6). (Remember ground is necessary, even if it is not shown in the circuit.)

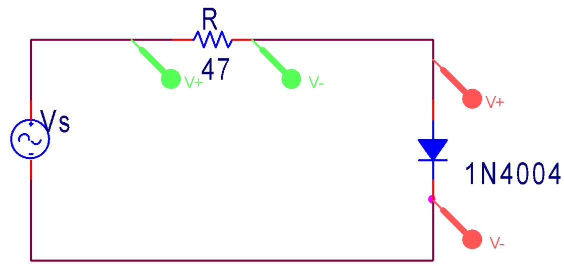

Figure 6: Diode with resistor circuit

Set the input voltage to a 100 Hz triangle wave with a maximum value of 2 V and a minimum value of –2 V. Measure the voltage across the diode and the voltage across the resistor on separate oscilloscope channels. Use math mode to determine the current through the resistor (which is equal to diode current) and plot diode voltage vs diode current (refer to the introduction for generating *xy* plots). You may need to adjust the vertical and/or horizontal scale to 'see' the plot.

Approximately, based on your plot, what is the turn-on voltage for this diode?

2. Set the input voltage to a 100 Hz, 30 mVpp (15 mV amplitude) sinusoidal wave with a 0.8 V DC offset. Identify the DC operating point of the diode (*i.e*. the DC average voltage and the DC average current). You can use the Measure Tab in the top center to add various voltage measurements. Measure the peak-to-peak AC voltage and peak-to-peak AC current of the sinusoidal components for the diode.

Determine the differential diode resistance ($r_D = V_{AC} / I_{AC}$) associated with the AC component. Draw the small-signal model of the circuit for this source voltage. How does r_D compare to an estimate of the slope of the I-V curve (see above, Part 2 of Pre-Lab Exercise 1) at the DC operating point? Is r_D consistent with your expectation?

3. Change the offset voltage to 1.5 V. Identify the diode's DC operating point (V_{DC} and I_{DC}), and the diode's AC values (V_{AC} and I_{AC}).

Determine the differential diode resistance ($r_D = V_{AC} / I_{AC}$) associated with the AC component. Draw the small-signal model of the circuit for this source voltage. How does r_D compare to an estimate of the slope of the I-V curve (measured above, under part 2) at the DC operating point? Is r_D consistent with your expectation?

Exercise 2: Rectifier circuits (optional)

1. Using the 1N4004 Diodes, build the half-wave rectifier circuit shown below (Figure 7). Set the source to a 4 Vpp, 250 Hz sinusoidal signal. Verify that the load voltage is consistent with expectations. Measure the average load voltage.

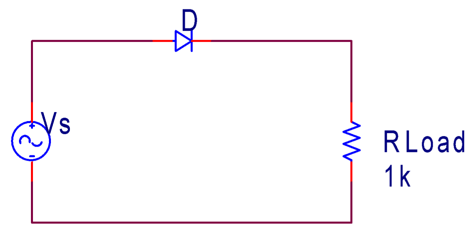

Figure 7: Half-wave Rectifier

Compare the load voltage levels when the diode is "ON" to the source voltage, is the diode behavior consistent with the Exercise 1 results?

2. Using the 1N4004 Diodes, build the full-wave rectifier shown below (Figure 8). Use a 1 kΩ resistive load. Set the source to a 4 Vpp, 250 Hz sinusoidal signal. Verify that the load voltage is consistent with expectations. Measure the average load voltage.

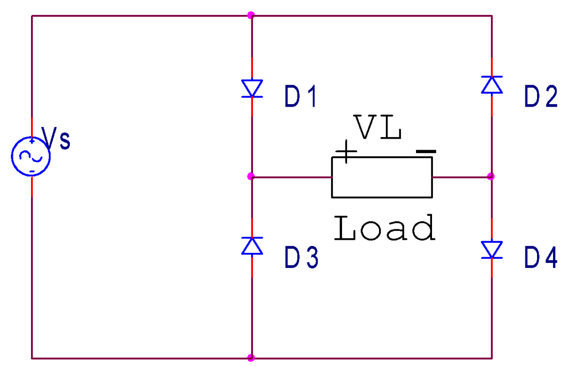

Figure 8: Full-wave rectifier circuit

Is the measured voltage consistent with expectations relative to the half-wave rectifier?

3. Add a 10 µF capacitor in parallel with the 1 kΩ resistive load. Electrolytic capacitors have a bias polarity, make sure you orient them correctly.

Compare the ripple voltage and average voltage to the theoretical values.

4. Replace the 10 µF capacitor with a 1 µF capacitor.

Explain the differences relative to the part 3 results.

Exercise 3: Zener diode characteristics

1. In Spice, build the circuit below (Figure 9). Use a DC voltage source for Vs and the D1N751 Zener diode in the DIODE library (refer to the introduction if you have not added the DIODE library). Sweep the source voltage from –1 V to 6.5 V and plot (versus source voltage) the current into the cathode of the diode. To sweep the voltage, select DC Sweep as your simulation type, pick the source by the name, and set the lower limit and upper limit. You should set the increment size so that your curve appears fairly smooth. Also, note that we are investigating the avalanche breakdown characteristics of the Zener diode when it is reverse biased.

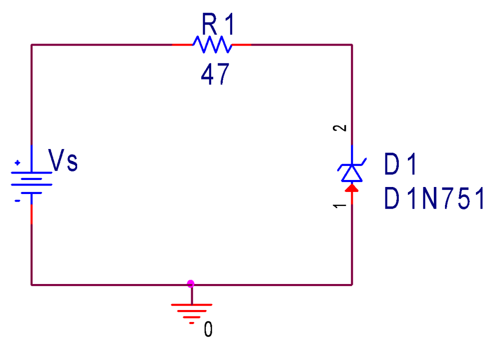

Figure 9: Zener diode circuit for PSpice

   Plot the diode current against the diode voltage. Note, the DC sweep sets the horizontal axis to the DC sweep voltage. You can set probes to make measurements in PSpice and then save the raw data to plot in Excel, Matlab, etc.

   a. Set a current probe at one of the circuit nodes (the current through each component is the same)
   b. Set a voltage probe across the Zener Diode
   c. Run the DC sweep
   d. On the Schematic window (plot window), select File in the upper right corner.
   e. Choose the Export option and save the data as a 'csv' file.
   f. Generate and I_{ZD}-versus-V_{ZD} plot using your favorite tool (ZD = Zener Diode)

2. Beyond the "knee voltage" and "knee current" the Zener diode is in reverse breakdown (commonly the desired operating regime). Estimate the Zener diode's knee voltage, V_{Knee}, and knee current, I_{Knee}.

   How does your PSpice value compare to the spec sheet values for the 1N751?

3. Determine the Zener diode's differential resistance (r_{ZD}) at (**i**) a reverse breakdown current of 1 mA and (**ii**) a forward current of 1 mA. Recall: $r_{ZD} = \mathrm{d}V/\mathrm{d}I$.

   Is the forward differential resistance consistent with the formula derived in class ($r_D = V_t / I$)? Compare the forward and reverse differential resistances. What are your findings?

4. Build the circuit below (Figure 10) using the LF351/353 op-amp. Set the source to a 8 Vpp (4 V amplitude), 100 Hz triangle wave (sawtooth-shaped wave). The non-inverting op-amp is implemented such that we can provide voltage signals to the load circuit in excess of the 5 V limit internal to the Discovery Board/Mobile Studio. Use a +15/–15 V voltage to power the op-amp.

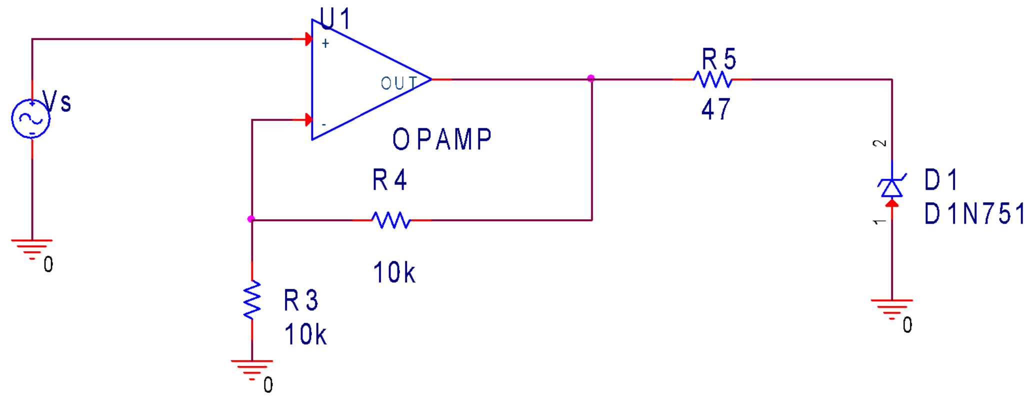

Figure 10: Experimental Zener diode circuit

As with Exercise 1, measure the voltage across the Zener diode and the voltage across the 47 Ω load resistor. Use the math mode to obtain I_{ZD}-versus-V_{ZD} plots for the Zener diode.

5. Download the raw data and obtain experimental estimates for the Zener diode's knee voltage (V_{Knee}) and knee current (I_{Knee}).

6. Estimate the Zener diode voltages when the Zener diode current is 5 mA and 10 mA. Use this result to get an estimate of the reverse breakdown resistance, r_{ZD}.

   Are your results consistent with the spec sheet values?

Exercise 4: Regulator circuits (optional)

1. Construct the circuit shown below (Figure 11) without the Zener diode. Use a 5 V amplitude sinusoidal source at 1 kHz. Measure the input voltage V_{in}, filtered voltage V_{Filter}, and output voltage V_{out}.

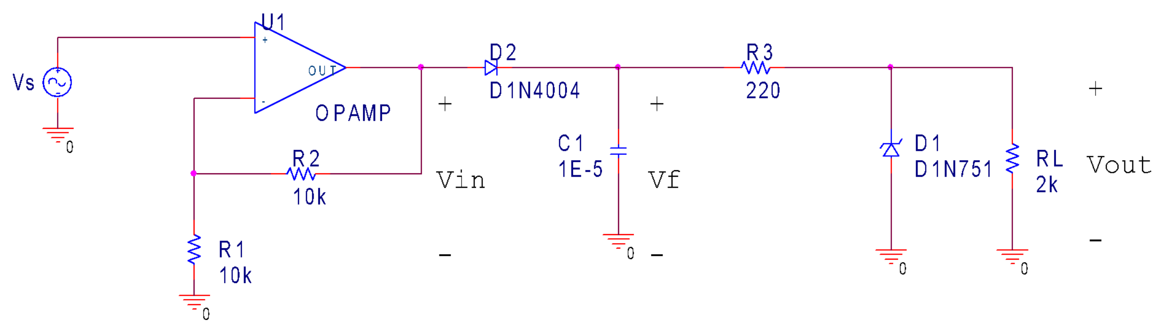

Figure 11: Voltage regulator circuit

Explain why the V_{in} voltage 'flattens out' during the on-time for the diode. The reason has been discussed in class.

2. Add the Zener diode to the circuit and repeat the measurements.

   Referring to the spec sheet for the 1N751, is the output regulated at approximately the Zener diode's breakdown voltage?

   Does the circuit meet the minimum voltage requirements over the full cycle, $V_{ZD} > V_{Knee}$?

   Does the V_{ripple} / V_{peak} ratio improve when the Zener diode is added?

3. Estimate and report the maximum and minimum current in the Zener diode I_{ZD} (the current through the diode at the points where the voltage across it is at a maximum and minimum). Hint: The current through the Zener diode is equal to the current through the 220 Ω resistor minus the current through the 2 kΩ load resistor. You can use the math channel to obtain this value.

   Using the spec sheet nominal current for breakdown, does the circuit meet the minimum current requirement, that is, $I_{ZD} > I_{Knee}$?

   Approximately determine the power consumed by R_3, R_L and the Zener diode? In the context of power consumed, what percentage of power is "wasted"?