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2024-02-07 (due 02-08)

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

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: $V_{RMS} = V_{Amplitude} / 2^{1/2}$

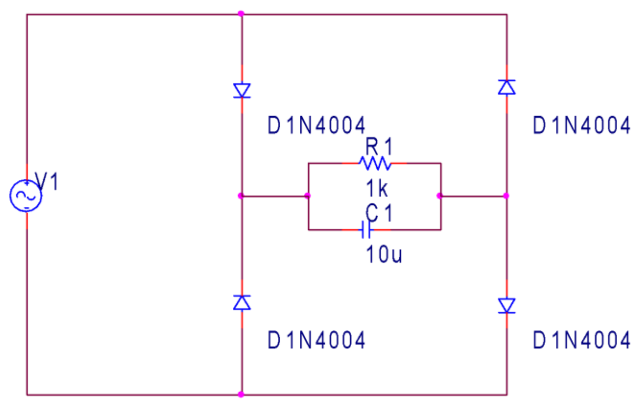
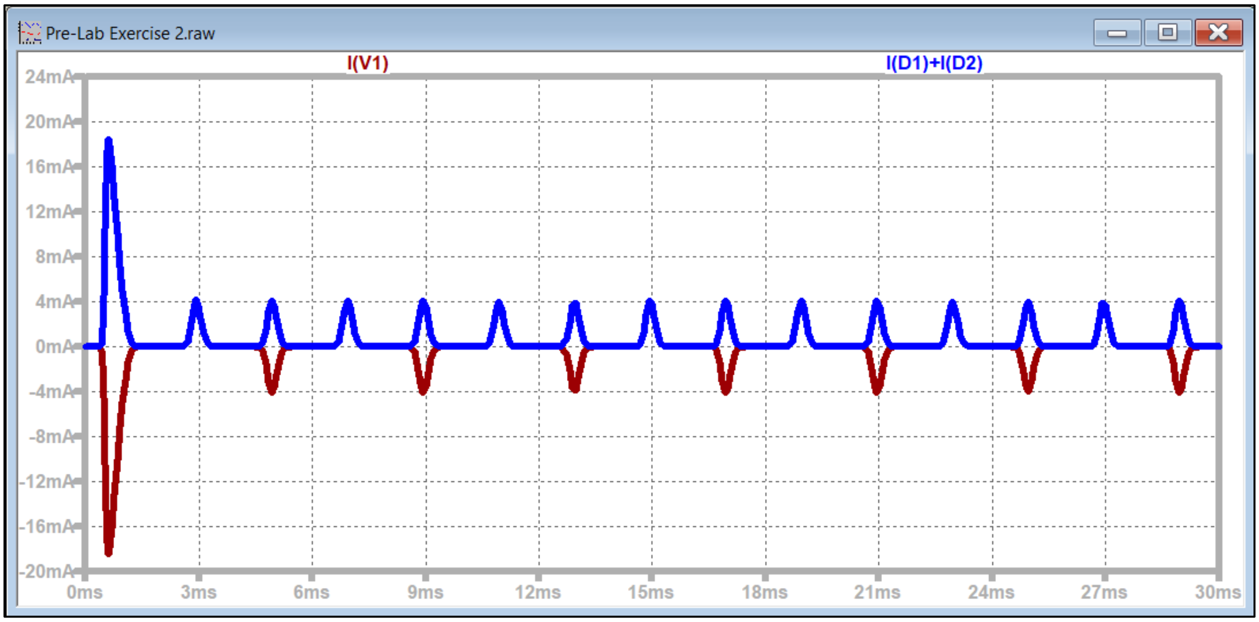


Figure 3: Diode rectifier bridge circuit

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.

Psource, avg = Vsource,rms * Isource,rms = (2v / sqrt(2)) * (($4.1*10^{-3}$ A)/sqrt(2)) = 4.1 mW

Psource avg = 4.1 mW

Pload, avg = Vload,rms * I load,rms = (1.31v / sqrt(2)) * (($4.1*10^{-3}$ A)/sqrt(2)) = 2.685 mW

Pload avg = 2.685 mW

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

Efficiency = 2.685 mW / 4.1 mW = 0.655 = **65.5% efficient**

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.

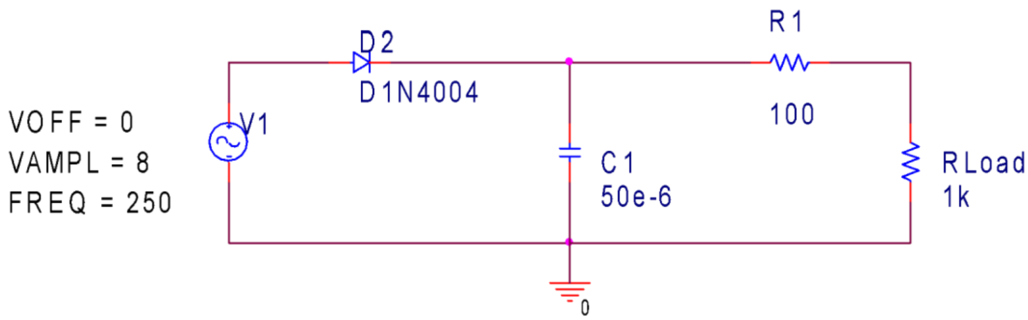
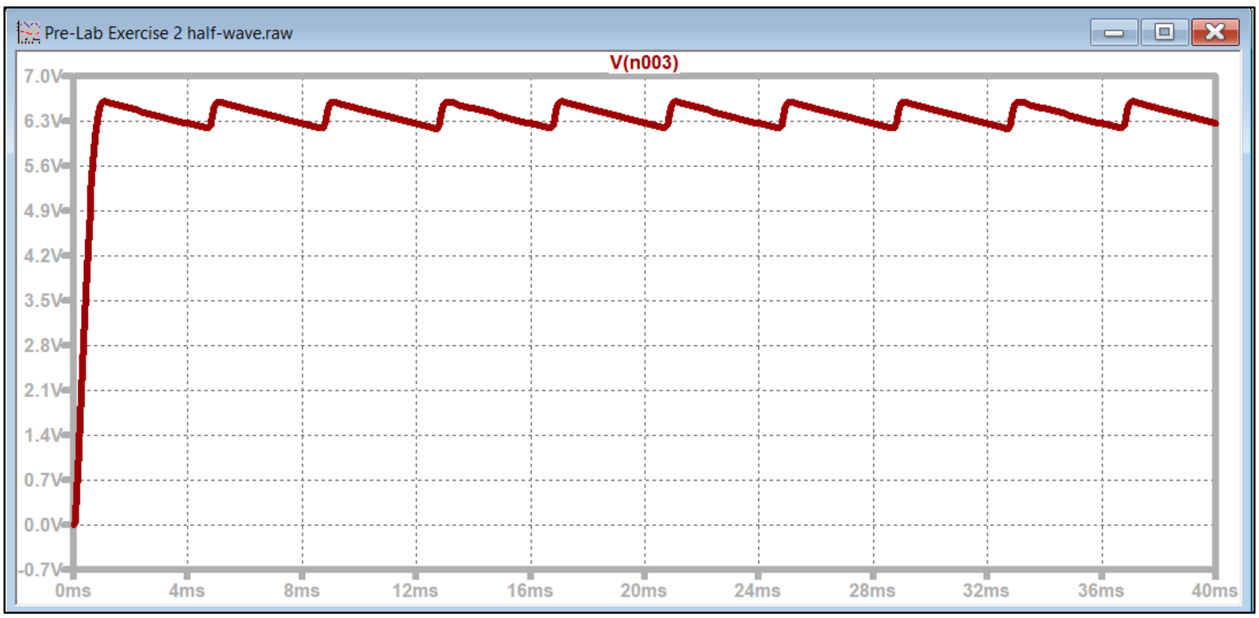


Figure 4: Diode circuit

Plot the load voltage versus time.



Estimate the average load voltage and the ripple voltage.

Vload,avg = around 6.3V

Ripple voltage has peak to peak waveform differential of 0.4v, so amplitude of 0.2v

Vload,ripple,pp = 0.4v

Vload,ripple,amplitude = 0.2v

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.

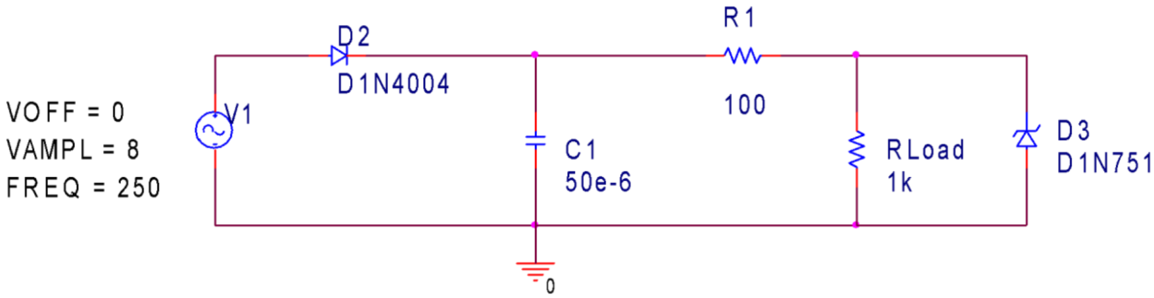
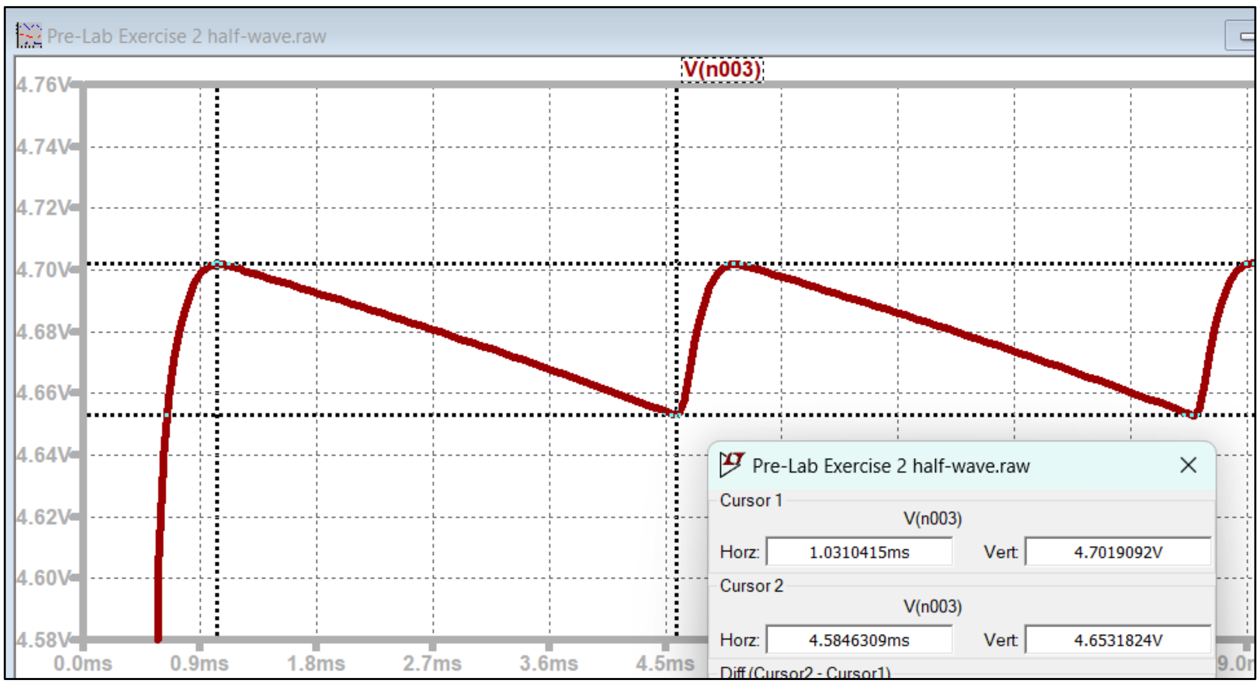


Figure 5: Diode circuit

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



Vload,avg = around 4.68V

Because the diode I chose in LTspice, the 1N750, has a Vz of 4.7V, the output waveform matches this. The 1N751 would result in a 5.1V output.

Ripple voltage has peak to peak waveform differential of 0.4v, so amplitude of 0.2v

Vload,ripple,pp = 0.0488V

Vload,ripple,amplitude = 0.0244V

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

Due to the Zener diode, the average load voltage is stabilized at its Vz=4.7V. For the 1N751, it would stabilize at Vz=5.1V. The ripple voltage is *greatly* decreased.

Exercise 3: Zener diode characteristics

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.

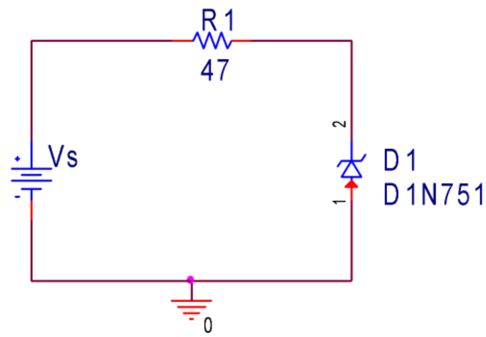
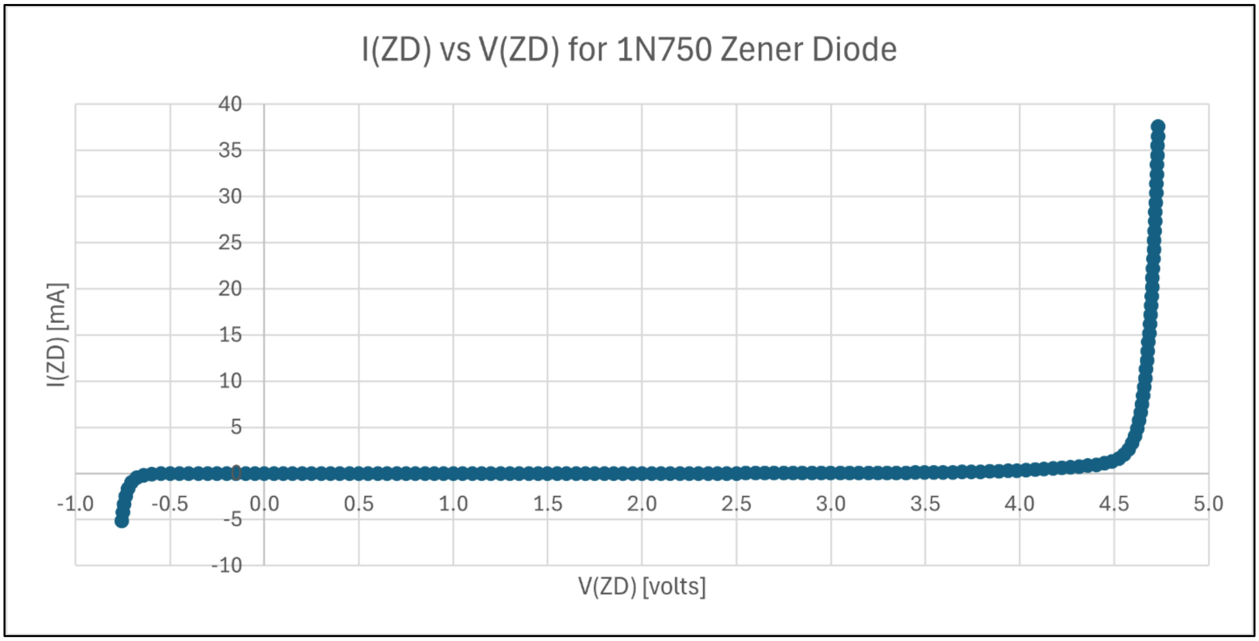


Figure 9: Zener diode circuit for PSpice

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)

Because the diode I chose in LTspice, the 1N750, has a breakdown voltage of 4.7V, the output waveform matches this. The 1N751 would result in a 5.1V output.



Here, I measured the voltage across the Zener Diode in regard to its reverse biased (breakdown) direction. So, when the voltage after R1 is 5v, that corresponds to a "-5v" applied to the conventional forward biased direction of the Zener diode. Thus, the current passed through the diode is "negative" in reference to the diode's normal forward bias direction. We can see that a +5v is applied to the cathode of the Zener, so that positive current flows from its cathode to its anode.

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}.

From the simulation and plot, the Zener diode's knee voltage and current are:

4.70	19.1955
4.70	20.2016
4.70	21.2104

$\boldsymbol{V_{knee} = 4.7\ V}$ $\boldsymbol{I_{knee} = \sim 20\ mA}$

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

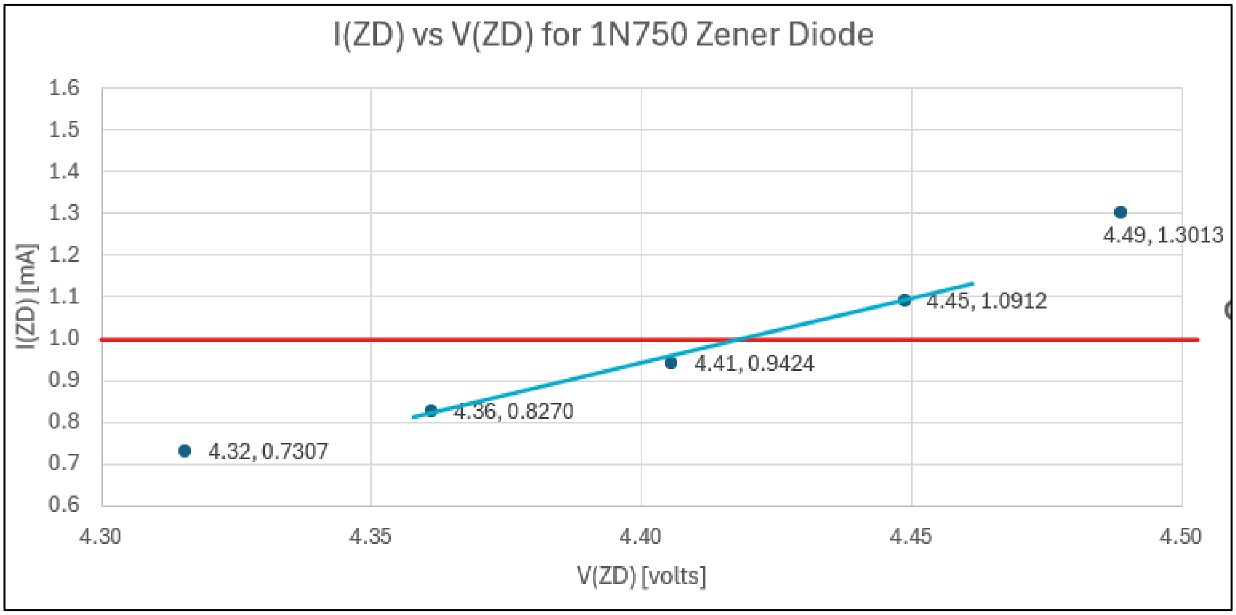
The spec sheet for the 1N750 I used in LTspice gives real values of:

$\boldsymbol{V_{knee,\text{spec}} = 4.7\ V}$ $\boldsymbol{I_{knee,\text{spec}} = 20\ mA}$

So, the LTspice simulation value matches the spec sheet value!

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: $r_{ZD} = dV/dI$.

i) For reverse breakdown current of 1mA:

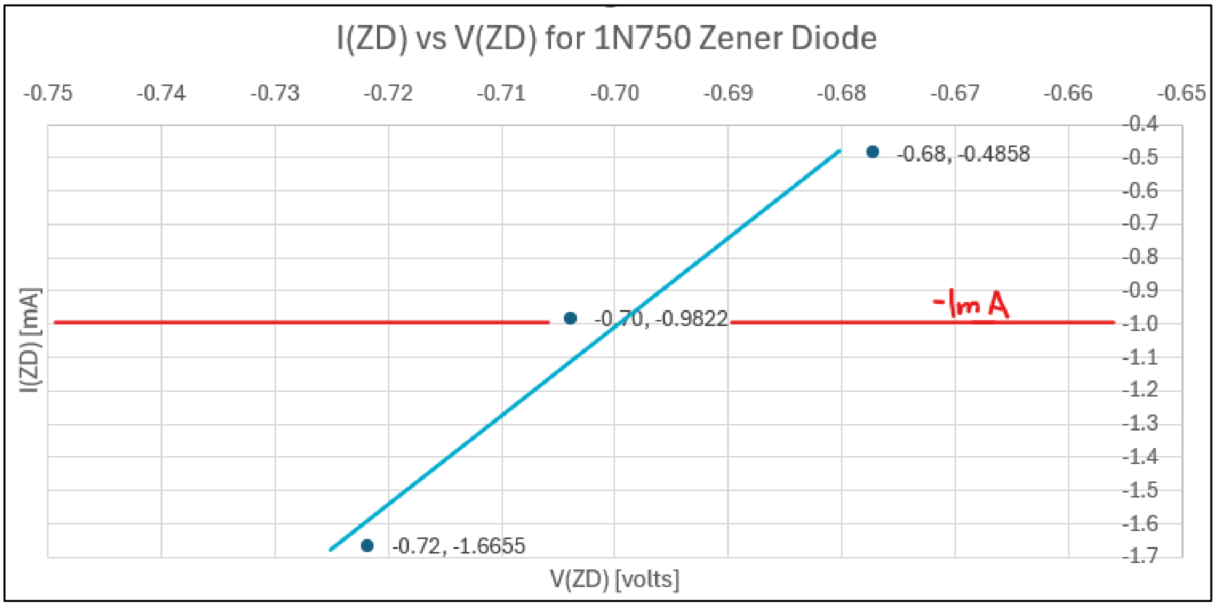


The graph has units of current I(ZD) in mA, so we'll be sure to convert:

$$r_{ZD,\text{reverse}} = \frac{dV}{dI} = \frac{(4.45 - 4.36)}{(1.0912 - 0.827) * (10^{-3})} = 340.65\ \Omega$$

$$\boldsymbol{r_{ZD,reverse} = 340.65\ \Omega}$$

ii) For forward current of 1mA:



The graph has units of current I(ZD) in mA, so we'll be sure to convert:

$$r_{ZD,\text{forward}} = \frac{dV}{dI} = \frac{(\text{-}0.68 \text{ - -}0.72)}{(\text{-}0.4858\text{- -}1.6655) * (10^{-3})} = 33.9\ \Omega$$

$$\boldsymbol{r_{ZD,forward} = 33.9\ \Omega}$$

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?

$$r_D = \frac{V_t}{I} = \frac{0.026V}{0.001A} = 26\ \Omega$$

My estimated value of $r_{ZD,forward} = 33.9\ \Omega$ is fairly close to this. By choosing different points for the calculation, I was also able to get a value of ~29 Ω.

The reverse differential resistance is about an order of magnitude greater than the forward differential resistance (340 ohms vs 34 ohms). This makes sense, because in order to achieve lower resistance in the reverse breakdown direction, we would need 4.7v. At a current of 1mA, the reverse voltage is too low in the reverse breakdown direction.

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.

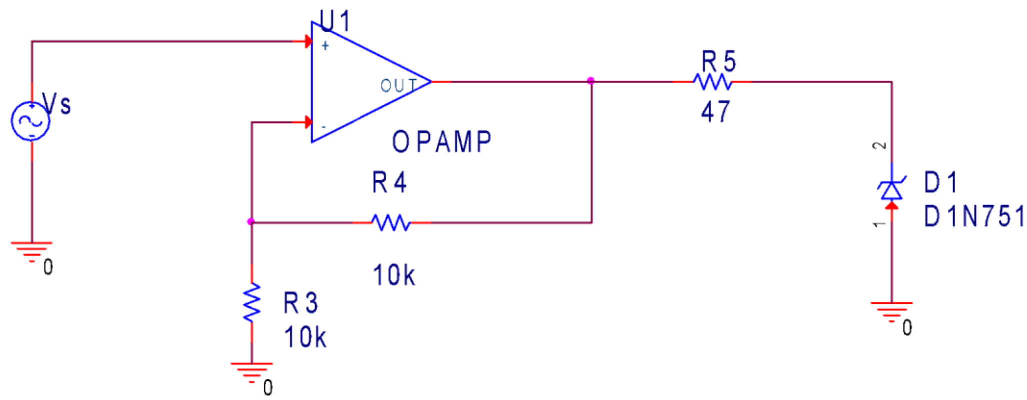


Figure 10: Experimental Zener diode circuit

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?