Nora Shao_L3A

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1 DC-DC Boost: Diode/Transistors, Loads, and Inductors

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Teammates at Table: [redacted]

Student Number: [redacted]

Lab Section: L3A

[2]:
```
# @title
%%capture
from IPython.display import Image
from google.colab import drive
import os
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

drive.mount('/content/drive/')
path = 'drive/My Drive/UBC ENPH Y2/ENPH259/Lab3/'
file_name = 'Nora Shao_L3A.ipynb'

assert file_name in os.listdir(path)

def img_path(img_name):
  return path + img_name
```

2 Prelab

2.1 Prelab Q1: Diode Test Circuit

Problem: Design a circuit and measurement procedure to measure the I-V relation of a diode with only the AD2, not a DMM.

Solution: We output a time-variant voltage through the AD2 as a triangular waveform (so the voltage rises and lowers steadily from 0 to peak voltage). Since the voltage drop across the resistor equals $I \times R$, and we know the resistor has a 100 Ω resistance, measuring the voltage drop across the resistor with the AD2's scope tells you the current running through the circuit as a function of time. We can also subtract the voltage across the resistor from the input voltage to get the voltage across the LED as a function of time.

We can compare the graph of this current against time with the (caculated graph of the LED's voltage against time to establish an I_d vs. V_d graph.

[3]:
```
Image(filename = img_path("L3A_Prelab1.jpg"))
```

[3]:

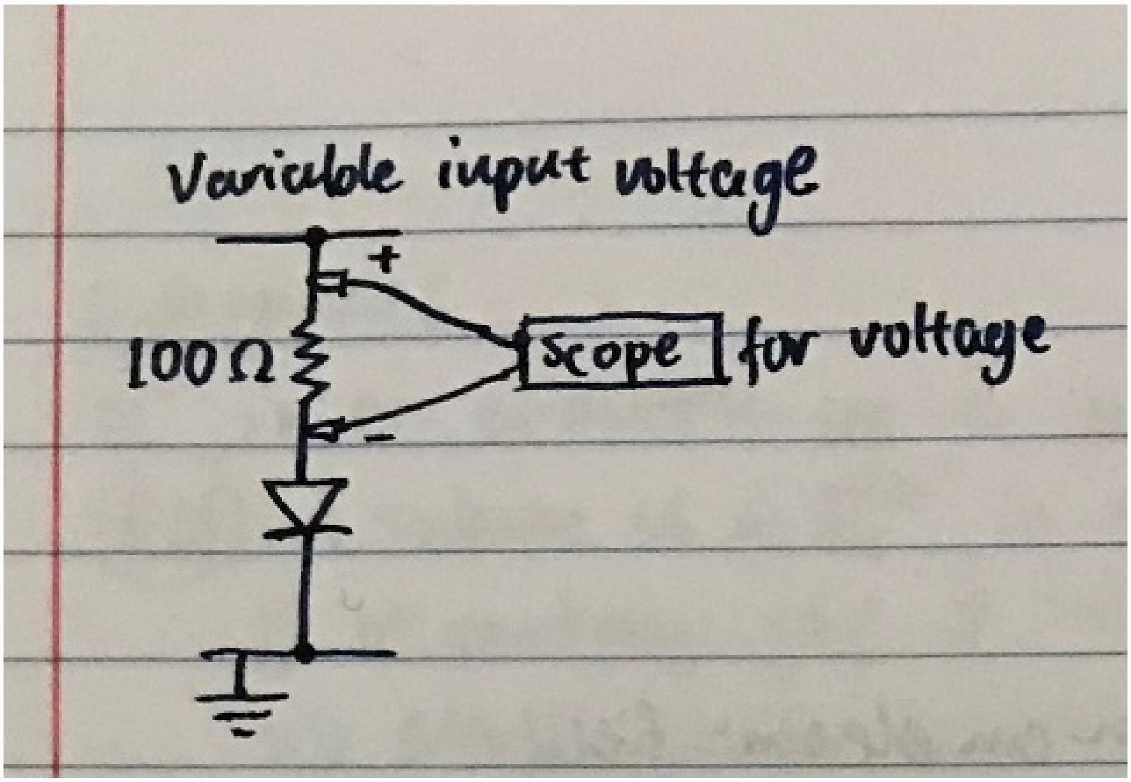


Figure 1: Circuit diagram for finding the I-V relationship of a diode with only the AD2

2.2 Prelab Q2: Transistor Test circuit

Problem: Using a VN2106 MOSFET design a switch to turn on and off an LED using the AD2's 5 V supply as the power source. Again don't forget to include a current limiting resistor and note that when forward biased the green LED will have a voltage drop of 2.5 V and the designed current for the LED is 0.2 mA.

Figure 2 depicts my design for a circuit that uses a MOSFET to turn on and off an LED. Because the voltage drop across the LED is 2.5 V and the input voltage from the AD2 is 5 V, the voltage drop across R1 must also be 2.5 V. We get the equation that

$$V_{R1} = 2.5V = R_1 \times 0.2mA,$$

which gives us

$$R_1 = 12.5k\Omega.$$

Since the MOSFET is n-channel, when it is off, the LED is off as no current flows through it. Looking at the datasheet, the threshold voltage of a VN2106 MOSFET is 0.8 V, so we set the V_G to 1 V, which we output using the same 5 V from the AD2 and a voltage divider constructed from a 4 $k\Omega$ and 1 $k\Omega$ resistor. Realistically, any combination of resistors that output a voltage slightly over 0.8 V will work.

[4]:
```
Image(filename = img_path("L3A_Prelab2.jpg"))
```

[4]:

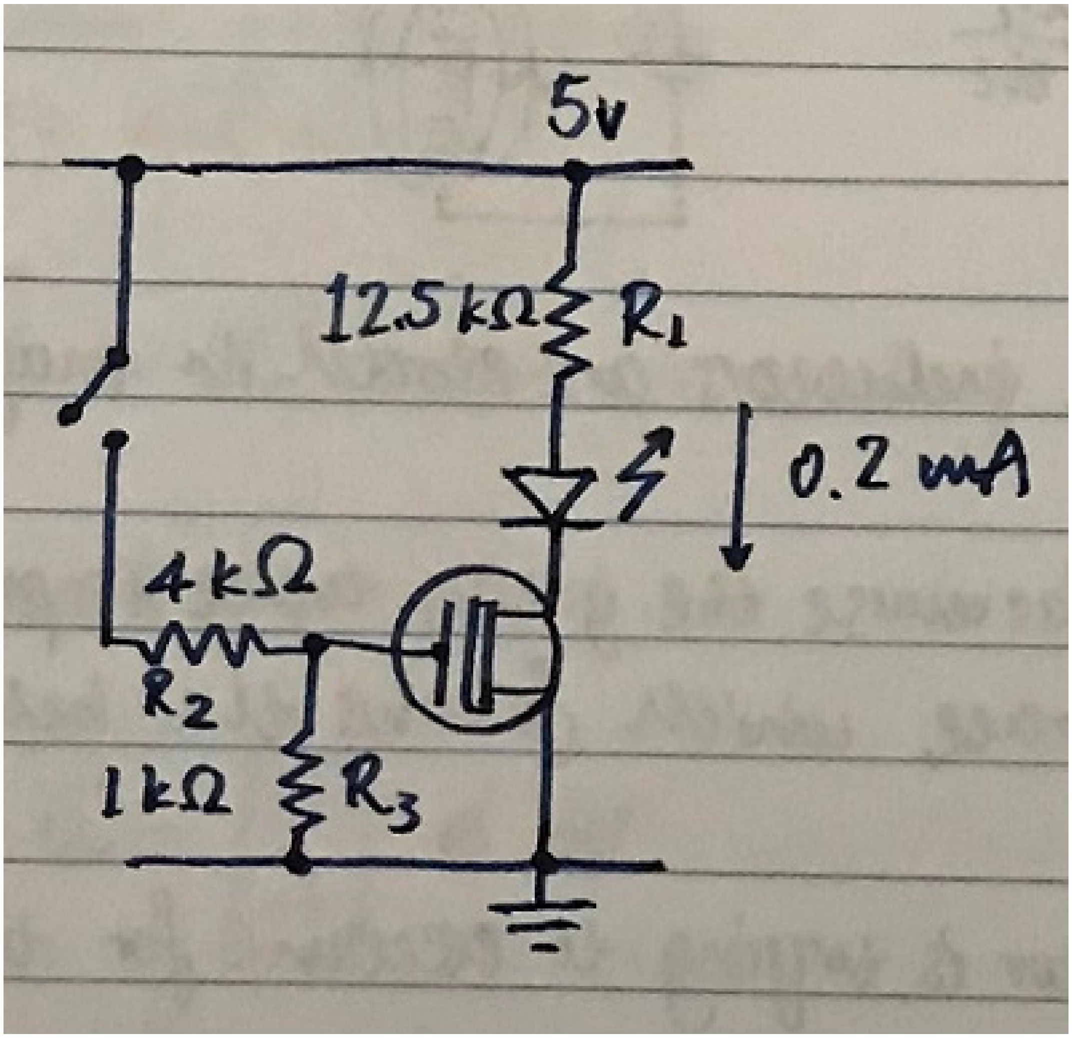


Figure 2: Circuit diagram for using a VN2106 MOSFET to control an LED

3 Troubleshooting

See sections for each part of the lab

4 Experiment: Diode

4.1 Ideal vs. non-ideal diodes

Goal: Construct a graph of the current-voltage relationship of the 1N4148 diode.

I am modifying my circuit design from Pre-lab 1 to make measuring the I-V relationship of a 1N4148 diode easier. Instead of doing calculations with the voltage over the resistor, I will just measure the voltage over the diode directly using another of the AD2's input channels.

Procedure:

- As I am using a 100 Ω resistor, for further accuracy, I use the DMM to measure its resistance as $99.0 \pm \frac{0.05}{\sqrt{3}}\Omega$.
- I have set up my circuit like the diagram in Figure 3, with a 100 Ω resistor in parallel with 1N4148 diode.
  - I have connected a BNC cable with the red probe powering the circiut (circuit) at the top of the resistor (R1) and the black probe below the diode, grounding the circuit. The cable is connected to the AD2's Wavegen 1 output, which outputs a triangular voltage that goes from 0 V to 2 V (1 V amplitude and 1 V offset) at a frequency of 50 Hz. This output is shown in Figure 5 (albeit the period should be 20 ms instead of 10 ms).
  - I am measuring the voltage across the resistor with the red probes from Scope (1+) and Scope (1-) and the voltage across the diode with the red and black probes from a cable connected to Scope 2+ (since the end of the diode is grounded already)
    * CH1 (orange) reads the voltage over the resistor and CH2 (blue) reads the voltage over the diode, on WaveForms
- To construct the graph of the diode's I-V relationship, I first add an X-Y plot on Waveforms with Y as the voltage over the resistor (as current through a resistor and thus circuit is proportional to the voltage drop over the resistor) and the X axis as the voltage over te diode. This is visible in Figure 7 and 8.
- Then I export the data from Waveforms and plot the voltage over the resistor divided by its resistance against the voltage over the diode, which gives us I_d vs. V_d.

[5]:
```
Image(filename = img_path('L3A_iv graph circuit.jpg'))
```

[5]:

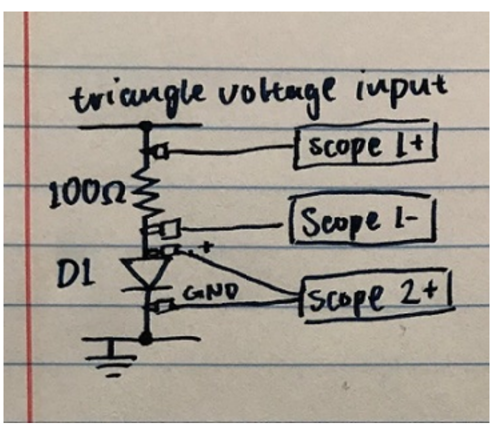


Figure 3: Circuit diagram of determining a diode's (D1) current-voltage relationship

[6]:
```
Image(filename = img_path('L3A_iv graph setup.jpg'))
```

[6]:

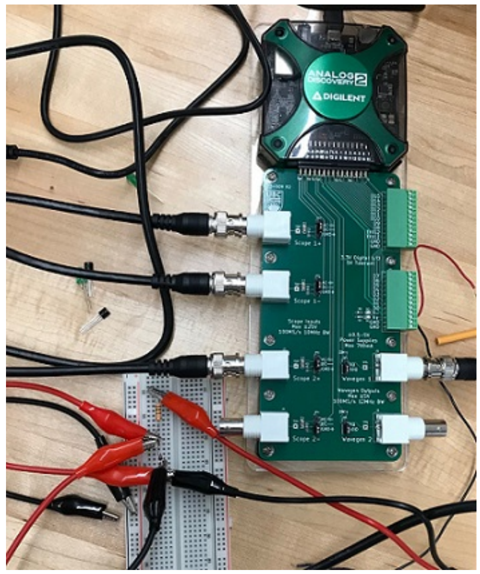


Figure 4: Breadboard circuit setup of determining a diode's (D1) current-voltage relationship

[7]:
```
Image(filename = img_path('Screenshot 2023-10-03 115646.png'))
```

[7]:

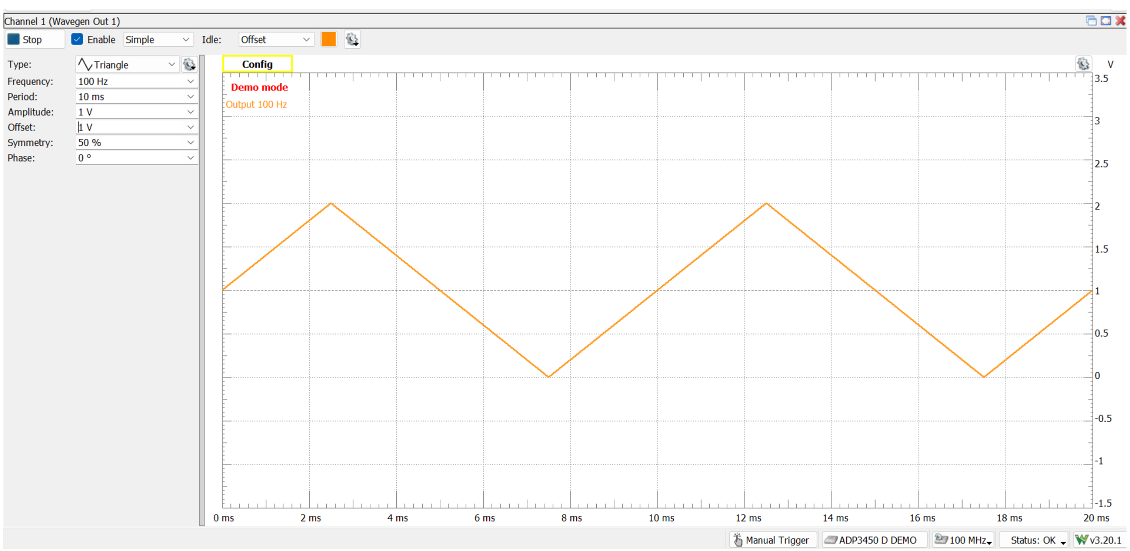


Figure 5: Triangle wave input to circuit

Results:

- I first observed the graph in Figure 6, with CH1 (orange) measuring what I thought was the voltage drop across the resistor and CH2 (blue) measured the voltage drop over the 1N4148 diode. The voltage drop over the resistor appeared significantly larger than the voltage drop over the diode, and the increasing and decreasing behavior of both followed the same pattern, which initially made sense to me. However, described in further detail in TS1, I realized this should not be the case and fixed my readings by checking the way I arranged the probes reading the voltages at different points of the circuit.
- Then I noticed a cap on the peaks of my resistor voltage (CH1 input), but I realized this was because when troubleshooting TS1, I had increased the input voltage past 5 V, which was the max voltage the AD2 could output, thus ‘capping’ the input waveform.
- See TS2 for more details on how I figured out the graph in Figure 8 wasn’t incorrect
- Finally, I figured out that Figure 8 was reading the correct values.
  - This made much more sense as the X-Y graph also showed a relationship closer to the I-V relationship depicted in Figure 9.

Troubleshooting

TS1: I realized I was reading the wrong voltages in Figure 5 after looking at the scales on the side, which showed that CH1 and CH2 were reading identical voltages when they were supposed to read the voltage over resistor and diode. I tried increasing the input voltage to see if that would make any noticeable difference, but the voltage input was capped at 5 V (hence the cap in Figure 6). In Figure 6, when I setup the voltage over resistor vs voltage over diode X-Y graph, I noticed the shape was off; the voltage over the diode rose too steadily in comparison with the voltage over resistor (the difference was more obvious when I got the correct X-Y graph in Figure 8), which of course, was because X and Y were the same.

Even though it appeared the voltage drop over the diode was much lower than the voltage drop over the resistor, which should be true, once I adjusted the two readings to the same scale, they were identical. With the TA’s help I checked my breakout board’s connections to the breadboard and realized that I had the probes for reading the voltage over resistor connected the wrong way, with Scope 1+’s positive probe connected to GND and Scope 1-’s positive probe connected to the top of the diode. The setup in Figure 6 actually depicts the probes connected in this incorrect fashion.

The shape of the two voltage readings being identical in shape (which should not be the case for a resistor and diode, explained in TS2) also should have alerted me to this issue.

TS2: Now I had the graph in Figure 7, with a floor on the bottom peaks of the channel reading the voltage over the resistor (orange). I thought that this was an issue I needed to fix, but the input voltage wasn't capped, so it couldn't be because of that.

Again, with the TA, I noticed that the voltage over the diode (blue) rose steadily while the voltage over the resistor stayed at 0 V until - at the same point, which the Y cursor highlights - the voltage over the diode started to plateau and the voltage over the resistor started to climb steaily. I realized that this was because resistors need a current for there to be a voltage drop across it, and the diode needed to reach a certain forward voltage until it allowed current to begin passing through the circuit and thus resistor. Thus, the input voltage had to climb to a certain level while the voltage over the diode also rose and the resistor's voltage drop stayed at 0, until the input voltage reached the diode's forward voltage. This wasn't really an issue, rather something I was supposed to see.

Understandings:

We see that the graph plotted is very similar to the I_d vs V_d graph provided in the Lab instructions for the prelab. However, instead of current rising at an unlimited rate vertically immediately as soon as the voltage across the diode reaches its forward voltage, the current takes time (albeit not a lot) to increase as the voltage over the diode increases, ore like the relationship shown in Figure 11, which depcits the I-V relationship of a non-ideal diode. This makes sense as realistically, the diode cannot act as a perfect short-circuit where infinite current can flow through. This goes hand-in-hand with our observation that the 1N4148 diode's forward voltage is greater than the 0 V that Figure 9 indicates as an ideal diode's forward voltage. Both of these observations are explained by the diode's internal resistance.

The diode's internal resistance also explains why Figure 8 shows that the voltage over the diode continues increase past its forward voltage, while the current increases almost exponentially relative to this voltage. While the current and voltage don't have a proportional relationship like normal resistors do, the resistance still means a real diode's voltage drop will increase as the current over it increases.

Moreover, the diode also doesn't act as a perfect open-circuit when not forward-biased. Although Figure 8 shows that up until the 1N4148's forward voltage, the current through the circuit stays at 0, provided with sufficient 'negative' voltage, diodes will have current leakage (much like the current leakage of a MOSFET described in the third part of the lab), where it does allow current to flow backwards through it.

[8]:
```
Image(filename = img_path('L3A_voltage across resistor and diode.png'))
```

[8]:

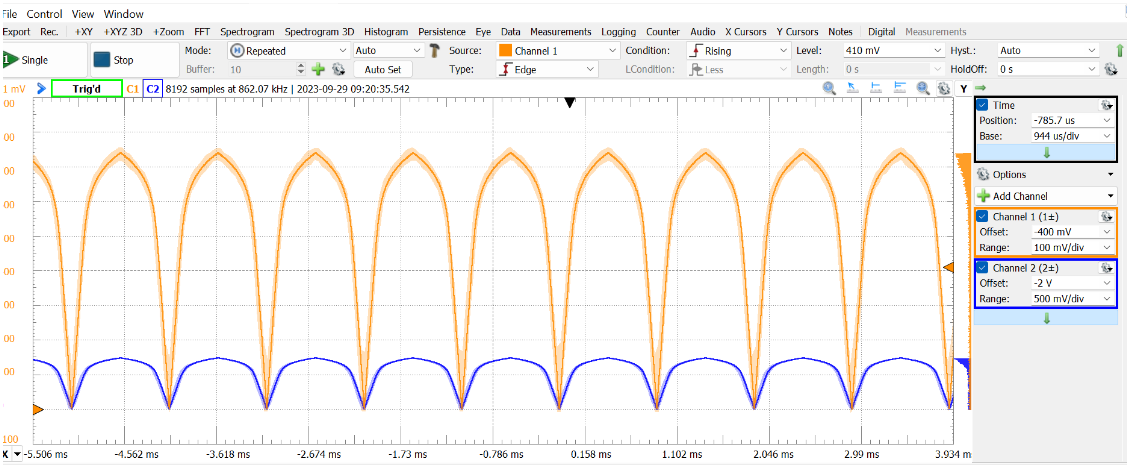


Figure 6: Initial (Incorrect) voltage over resistor (orange) vs. voltage over diode (blue) vs. time scope graph

[9]:
```
Image(filename = img_path('L3A_scope xy graph.png'))
```

[9]:

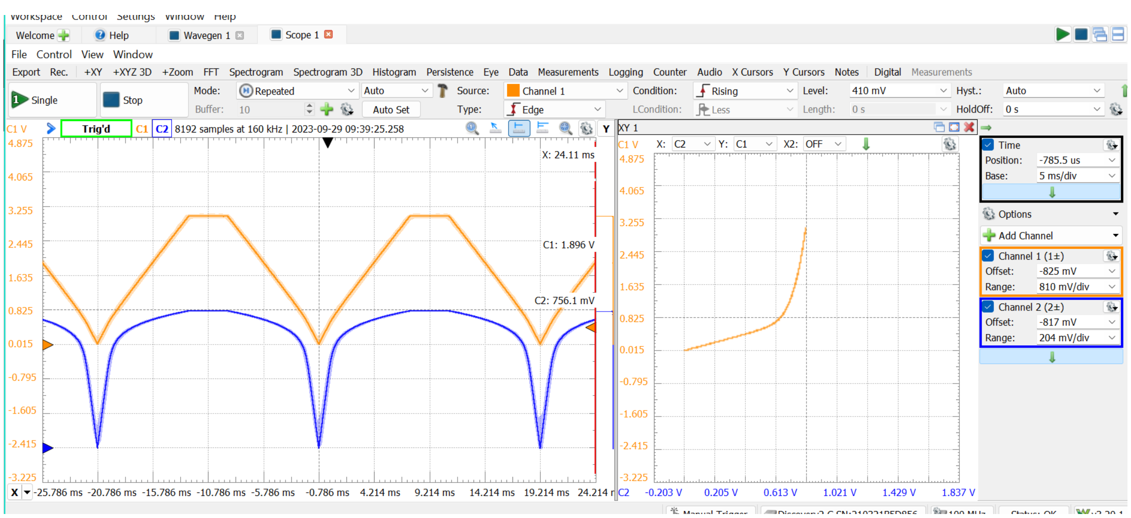


Figure 7: Voltage over resistor and diode with capped input voltage

[10]:
```
Image(filename = img_path('L3A_correct scope xy graph.png'))
```

[10]:

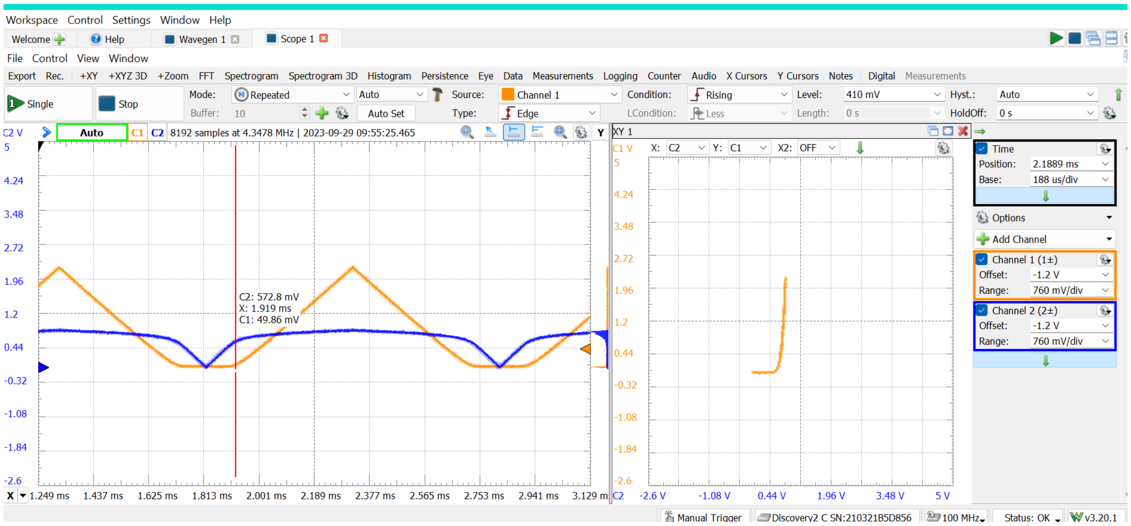
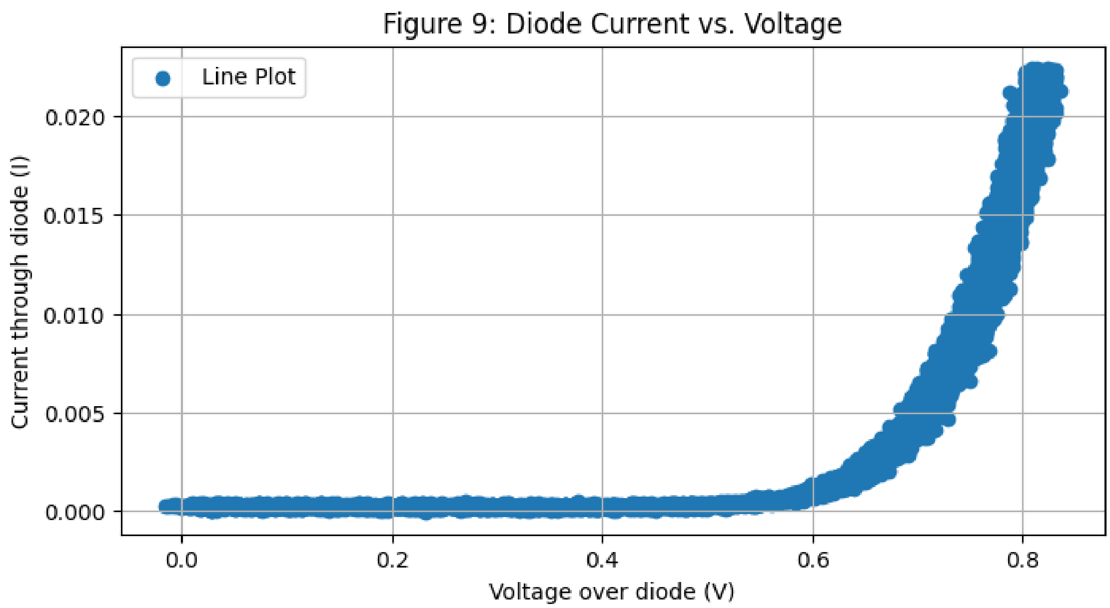


Figure 8: Corrected voltage over resistor (orange) vs. voltage over diode (blue) vs. time scope graph

[11]:
```
ivGraph = pd.read_csv(img_path("L3A_I-V data.csv"))
#print(ivGraph)
resistor = 99

ivGraph['Channel 1 (I)'] = ivGraph['Channel 1 (V)']/resistor

plt.figure(figsize=(8, 4))
plt.scatter(ivGraph['Channel 2 (V)'], ivGraph['Channel 1 (I)'], label='Line␣
↪Plot')
plt.xlabel('Voltage over diode (V)')
plt.ylabel('Current through diode (I)')
plt.title('Figure 9: Diode Current vs. Voltage')
plt.legend()
plt.grid(True)
plt.show()
```



[12]:
```
Image(filename = img_path('L3A_ideal iv graph.png'))
```

[12]:

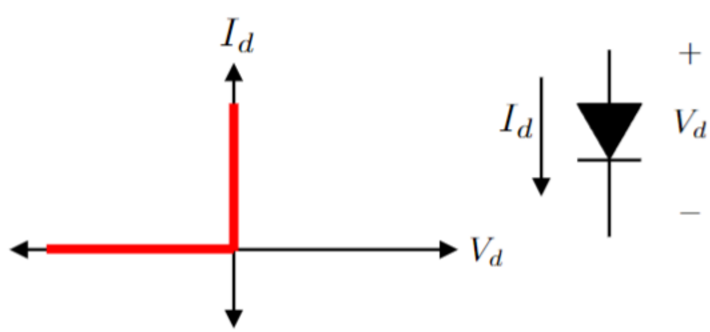


Figure 10: I-V relationship of an ideal diode

[13]:
```
Image(filename = img_path('5175b518ce395f2d49000000.png'))
```

[13]:

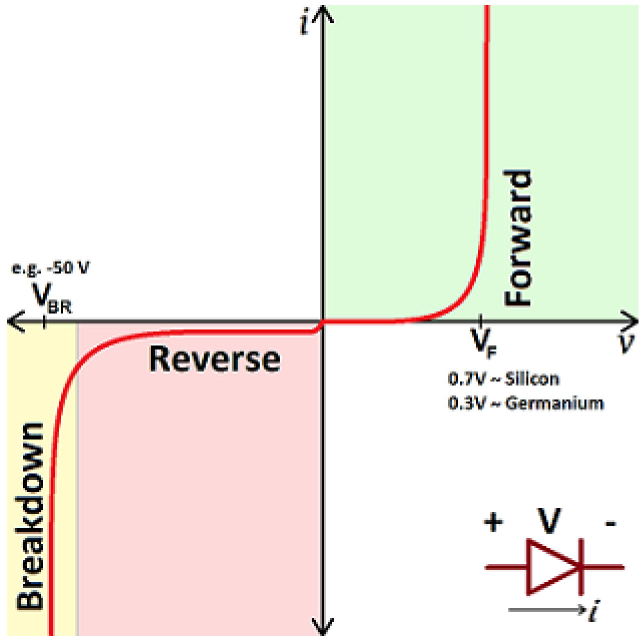


Figure 11: I-V relationship of un-ideal diodes

4.2 Rectified Sine Wave

Goal: Recreate the rectified sine wave image provided in the lab instructions with a resistor-diode circuit.

You can take advantange of the non-ideal diode's non-zero forward voltage to truncate voltage readings that require current at input voltages below a certain threshold,

Procedure:

- I start by setting up the circuit on the breadboard like in Figure 12. The setup is depicted in Figure 13, where I have Scope 1+ and Scope 1- reading the voltage across the resistor
  - The majority of the voltage drop across the circuit from the input will occur over the resistor.
- I use WaveForm's wavegen output to output a sine wave at 100 Hz, and connect this output via a BNC cable's red probe to the top leg of the resistor, and I use the black probe to ground the circtui.
- For the offset I needed to set for the input sine wave to get the ~50% duty cycle sine wave provided in the lab instructions, I examined Figure 9 to find the forward voltage of the 1N4148, which I determined to be ~0.6 V.
  - This way, you actually get a rectified sine wave reading, as the input signal accounts for how the diode effectively sets the 0 V (when current starts flowing and resistors get a voltage drop across) of the circuit to its own forward voltage.

- I initially set the input voltages amplitude to 1, but the output reading over the resistor had an amplitude at around 0.8 V, so I remembered there was a slight voltage drop over the diode and increased the input amplitude by trial and error to 1.15 V until the resistor voltage drop was also 1 V.

[14]:
```python
Image(filename=img_path('L3A_rectified sine circuit.jpg'))
```

[14]:

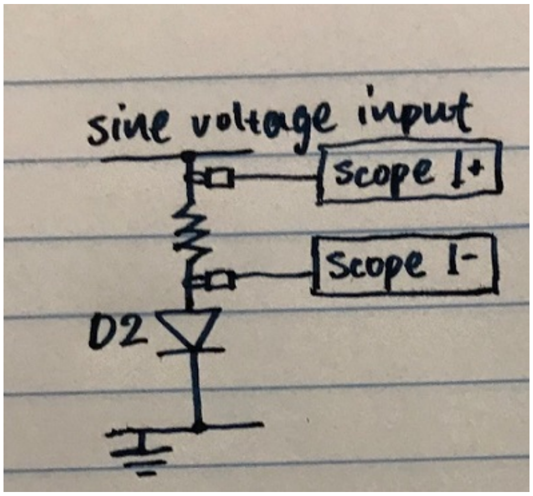


Figure 12: Updated circuit diagram for creating a rectified sine wave

[15]:
```python
Image(filename = img_path('L3A_rectified sine wave setup.jpg'))
```

[15]:

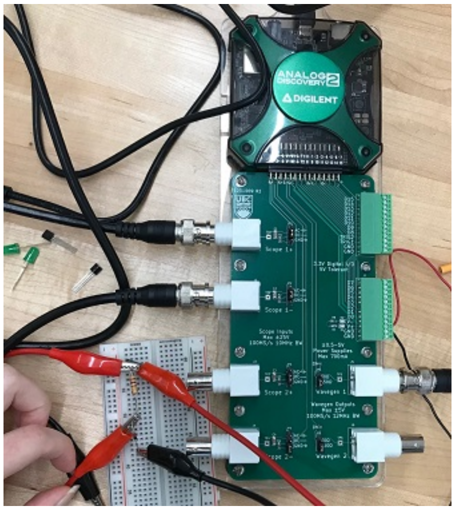


Figure 13: Circuit setup on breadboard for reading recitified sine wave

[16]:
```python
Image(filename = img_path('Screenshot 2023-10-03 115019.png'))
```

[16]:

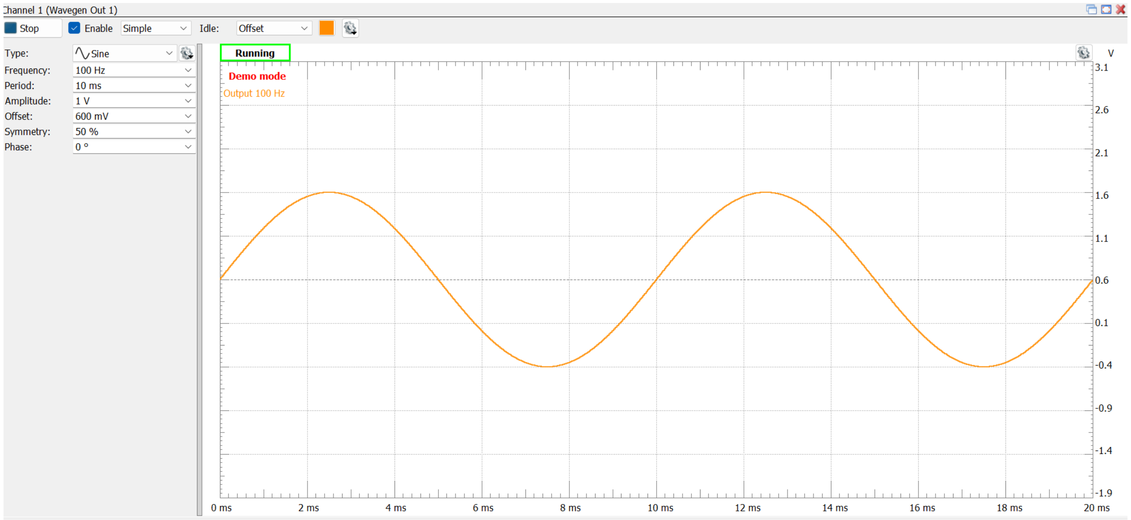


Figure 14: Input sine wave voltage I applied to the resistor-diode circuit

Results: Immediately on Waveforms, I had the shape of a cut-off sine wave seen in similar to the one in Figure 15, but the peak voltage was at around 0.8 V rather than 1 V and I had to use trial-and-error on the amplitude of the input wave to get a peak of 1 V over the resistor.

I experimented with the input sine wave voltage's offset and found different periods of on and 'off' being read on the scope as the voltage over the resistor, since more or less of the input voltage was actually being read instead of being blocked by the diode's forward voltage.

Understanding: I accounted for the non-ideal behavior of the 1N4148 diode by using its non-zero forward voltage to rectify the sine wave. The resistor requires current for a voltage drop, and the input sine wave voltage needs to reach the forward voltage threshold of a resistor before current starts going through the circuit and the scope starts reading a voltage in a resistor, hence

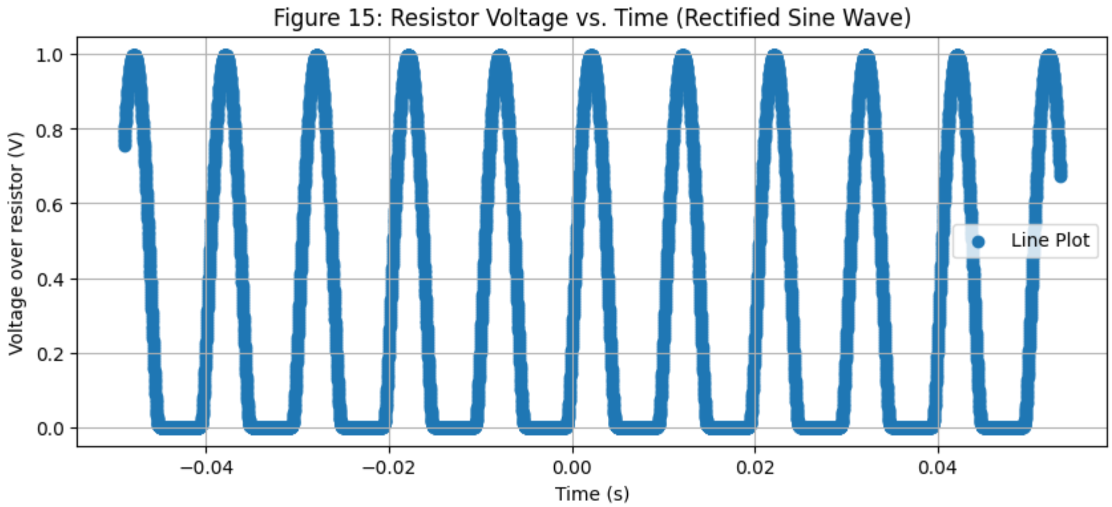
As well, to get a peak of 1 V in Figure 15, I also had to consider the diodes non-zero forward voltage by setting the input sine wave's voltage to 1.15 V, so even if there was always a small voltage drop across the diode, the voltage drop across the resistor still peaked at 1 V.

[17]:

```
rectifiedSine = pd.read_csv(img_path("L3A_rectified sine wave.csv"))
#print(rectifiedSine)


plt.figure(figsize=(10, 4))
plt.scatter(rectifiedSine['Time (s)'], rectifiedSine['Channel 1 (V)'],␣
  ↪label='Line Plot')
plt.xlabel('Time (s)')
plt.ylabel('Voltage over resistor (V)')
plt.title('Figure 15: Resistor Voltage vs. Time (Rectified Sine Wave)')
```

```
plt.legend()
plt.grid(True)
plt.show()
```



4.3 Milestone

- Completed

5 Experiment: MOSFET

Checking MOSFET:

- I first used the diode setting on the DMM to check the voltage from the source to drain of the MOSFET, which was ~0.6 V, within the reasonable 0.4-0.9 V described at https://electronicsbeliever.com/how-to-know-if-mosfet-is-defective/. However, when I switched the placement of the probes around, I had no reading from the DMM
  - The occurs because the diode function on the DMM reads a voltage by applying a current through the MOSFET that can only flow through a closed MOSFET when it is flowing from the source to drain, while the gate prevents current flowing from source to drain. 'Off' n-channel MOSFETs cannot block current flowing backwards, only current flowing from drain to source.
- The resistance between each of the terminals (which I also measured using the DMM) was also in the $M\Omega$s, which makes sense, as when there is no voltage over the threshold voltage of the MOSFET's gate, the MOSFET should (ideally) act as an open circuit. A component with a very large resistance is the unideal version of this open circuit.

Procedure:

- I roughly followed my setup in Figure 2 on the breadboard, but for convenience, I added 12 $k\Omega$ in series with the LED rather than 12.5 $k\Omega$, as we don't need exactly 0.2 mA running through the circuit anyways. I also didn't use a voltage divider to apply a voltage to the gate just over
  - The modified circuit schematic and setup on the breadboard are shown in Figures 16 and 17
  - To properly orient the MOSFET in the circuit, I read the datasheet of a VN2106 MOSFET here: https://ww1.microchip.com/downloads/aemDocuments/documents/OTH/ProductDocuments/DataSh
- I connected a jumper wire from the AD2's voltage supply to the top of the circuit on the breadboard and two wires from each of the breakout boards' GND ports. One grounded the circuit at the MOSFET's source leg and the other I clipped the grounding strap around my wrist to.
  - On Waveforms, I set the voltage supply to 5 V.
- For the gate voltage source, I attached a jumper wire to the same row on the breadboard the power jumper wire was inserted into. This also acted as the switch, which I would 'close' by inserting into a terminal on the same row as the gate leg of the MOSFET. Figure 17 shows the gate closed and the LED on via this connection.

[18]:
```
Image(filename = img_path("L3A_MOSFET circuit.jpg"))
```

[18]:

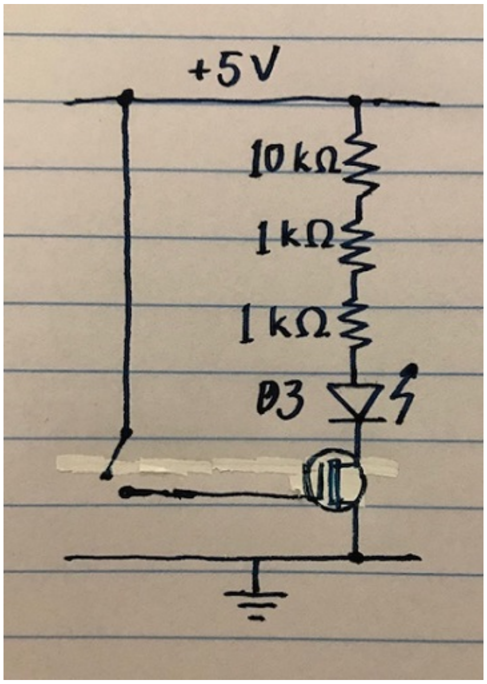


Figure 16: Updated circuit schematic for a MOSFET-controlled LED

[19]:
```
Image(filename = img_path("L3A_MOSFET gate closed setup.jpg"))
```

[19]:

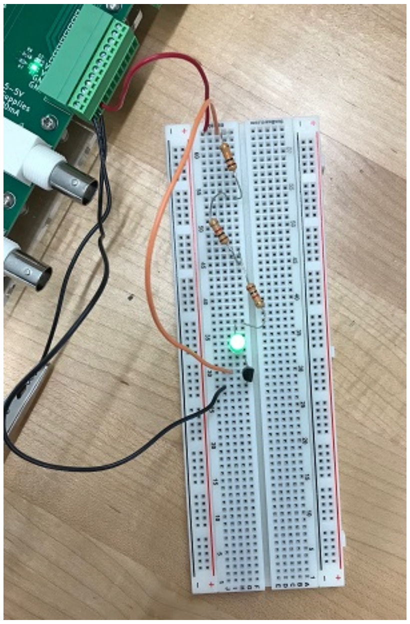


Figure 17: Closed MOSFET gate with lit up LED on breadboard

[20]:
```
Image(filename = img_path('L3A_MOSFET floating gate setup.jpg'))
```

[20]:

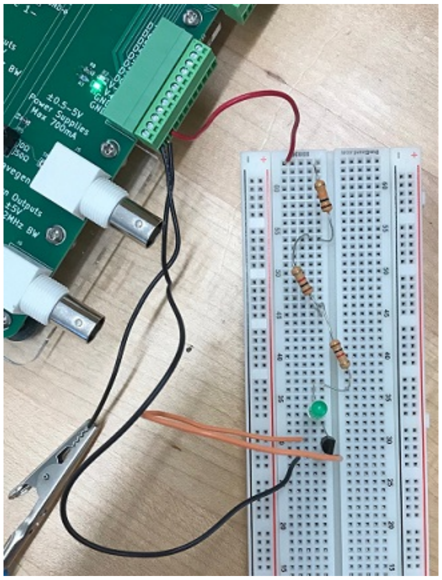


Figure 18: Unconnected voltage source connected to MOSFET gate

Results/Observations:

1. The gate voltage source (orange wire) indeed turns the LED on and off depending on when I connect its bottom end to the MOSFET's gate, but a more accurate description is that it turns the LED brighter when connected, because when no voltage was connected to the gate, the LED was still on very dimly.
2. When I unconnect the top end of the gate voltage source from the power rail and leave it in the air, the LED stays on, but decreases signficiantly in brightness. Figure 17 shows the small light in the LED.
3. When I hold the unconnected end of this wire with one hand, and touch Hobbes or my tablemate with my other hand, the LED briefly flares a little brighter. If I touch another component above the LED, the LED immediately brightens. Meanwhile, if I touch any grounded wire or part of the circuit, the LED shuts off completely (instead of just dimming like when I disconnect the gate voltage source).

Understandings:

1. The LED is still partially on because we don't expect our MOSFET to act like a perfect open-circuit (similarly to how a forward-biased diode isn't actually a perfect short-circuit). Rather, in reality, it is more like a very large resistor, and there is still a little current leaking through it that allows the LED to turn on (albeit only very dimly since the leakage current is low). So the behaviour of the LED makes sense.
2. The same reason the LED stays on dimly with nothing, not even a wire connected to the MOSFET's gate, applies to the scenario with a floating wire connected to the MOSFET. The leakage current still flows through the MOSFET and LED to ground
3. What this exercise showed me is that MOSFETs are incredibly sensitive to the smallest voltages. Even if I leave a wire connected to the MOSFET's gate but unconnected to anything else, there is still a little current passing through the LED and MOSFET. Just the static electricity I built by rubbing Hobbes or touching a teammate added enough voltage to the MOSFET to brighten the LED briefly. However, as soon as I grounded the unconnected end of the orange wire, the LED shut off completely, as the grounding ensured there was no stray voltage entering the MOSFET's gate terminal and the leakage current would all flow to ground rather than through the LED. Thus, it's safest to always ground the gate terminal when not actively using the MOSFET as a switch.

6 Conclusion

6.1 Ideal vs. non-ideal Diodes

In this part of the lab, we understood the behaviour of real diodes in circuits.

I measured the current through a 1N4148 diode and the voltage drop against it and plotted the current against the voltage to establish the I-V relationship of a real diode. I compared this I-V relationship (Figure 9) with the I-V relationship of an ideal diode (Figure 10) and discovered the a real diode behaves similarly to an ideal diode, with two main differences:

1. The current through our diode doesn't immediately increase at an unlimited rate as soon as the input voltage reaches its forward voltage. As well, the forward voltage across the diode actually increases as current increases, instead of staying constant.

2. The forward voltage of our diode was not 0. Instead, it was close to 0.6 V. Under a forward biased condition, ideal diodes should act as a perfect short-circuit, but real diodes have a low voltage drop.

It is important to note that real diodes have internal resistance that prevents them from behaving like ideal diodes, which act as perfect short-circuits when forward biased and perfect open-circuits when the input voltage is non-positive.

6.2 Diode-based Rectifier

Here we took advantage of our learnings about the non-ideal behaviour of diodes in the previous section to construct a signal rectifier.

We used the forward voltage of the 1N4148 diode we had previously experimented on to essentially 'truncate' the bottom half of an offsetted input sine wave voltage. We measured the voltage over the resistor to get a graph like the one in Figure 15. To ensure we have a 50% duty cycle (or 'symmetric') rectified sine wave, we offset the input sine wave to the forward voltage of the diode we had determined in the previous part of the lab, in Figure 9. However, we also had to account for the diode's small voltage drop, since it didn't act as a perfect short circuit, by increasing the input voltage slightly over 1 V, which is the max voltage we wanted over the resistor.

This part of the application introduced us to a real-world application of components like diodes. Because they only allow current to flow through in one direction, it blocks any current from running through the circuit (and thus voltage drop across the resistor) when the input voltage drops below the diode's forward voltage.

6.3 MOSFETs

In the final part of the lab, we used a VN2106 MOSFET as a switch to control an LED. I first used my understanding of how MOSFETs work to ensure my MOSFET *did* work; I used the DMM to ensure the unconnected MOSFET had a large resistance between all terminals since this should effectively make it an open circuit when it's off, and to check that the MOSFET could only block current flow from drain to source when off. As well, we had to ground ourselves via a conducting wrist strap for safety purposes due to MOSFETs' ease of blowing.

I constructed the circuit I designed in the prelab (with slight changes) and used it to experiment with the different behaviour of the LED at different MOSFET modes. I found that MOSFETs are very sensitive to the smallest voltages by watching the LED brighten when I touched someone or especially another ungrounded part of the circuit while touching a wire connected to the gate, which is why it is safest to keep the gate grounded when not actively using the MOSFET.

This experiment introduced us to how MOSFETs are actually used and potential safety practices when handling them as well as other circuit components in the industry.

[21]:
```
# @title
%%capture
!apt-get install texlive-xetex texlive-fonts-recommended texlive-latex-recommended texlive-plain-generic pandoc
```

[22]:
```
# @title
# Capture to prevent lots of output... Remove this if troubleshooting!
%%capture

pdf_file_name = file_name.split('.')[0]+'.pdf'  # Same as file_name with .ipynb changed to .pdf
!rm $file_name
!rm $pdf_file_name

import os

full_path = os.path.join(path, file_name)
!cp  "$full_path" ./

!jupyter nbconvert "$file_name" --to pdf
```