Electro-Optic Transducers

Photoconductors

Of the electro-optic transducers we will be working with, only the photoconductor, shown in Figure 3-3, is a linear device. That is, the current versus voltage response is linear and bidirectional. The photoconductor behaves as a resistor whose value changes with illumination.

The photoconductor is governed by the equations

$$R_p = 1 / G_p \quad \text{and} \quad G_p = G_0 + \alpha I$$

where G_0 is the dark conductance ($1 / R_0$). Different types of photoconductors will have different dark conductances. Shining light onto the photoconductor will lower the resistance of the device.

Measure the resistance of the photoconductor in darkness and in bright light.

Photoconductor Resistance

In darkness: 18, 000 Ohms

In bright light: 1, 3000 Ohms

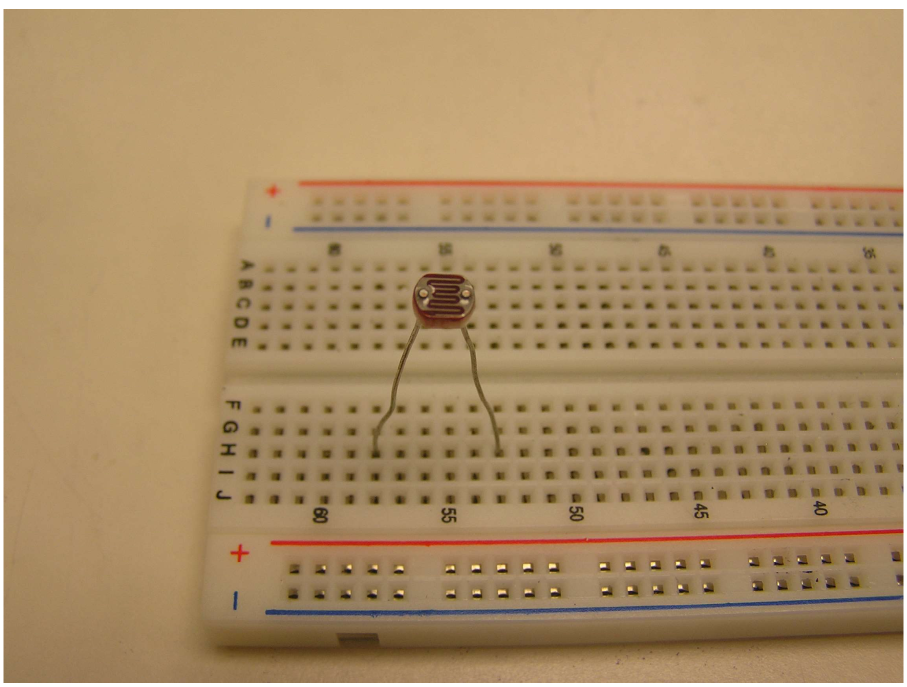


FIGURE 3-3: Photoconductor

Light-Emitting Diodes (LEDs)

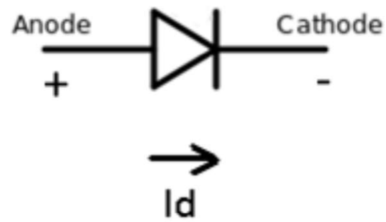


FIGURE 3-4: Diode Symbol

Diodes, also known as p-n junctions, are devices that do not follow Ohm's Law. Diodes have a non-linear relationship between current and voltage. Diodes are typically represented in diagrams by the symbol shown in Figure 3-4. The anode is also called the "positive side" and the cathode the "negative side". We first define I_d, the current flowing through the diode, as flowing from the anode to the cathode. In Figure 3-5, the diode is forward biased—that is, the anode is at a higher voltage than the cathode. We can see that under forward bias, the current-voltage relationship is exponential. In Figure 3-6, the diode is reverse biased, with the cathode at a higher voltage than the anode. The diode allows negligible current to pass under reverse bias.

A reasonably accurate mathematical model of the current-voltage relationship is:

$$I_d = I_0 \left(e^{V/Vt} - 1\right),$$

where V_t is known as the thermal voltage and is typically around 0.026 Volts and I_0 is known as the saturation current. The saturation current is typically only a fraction of a microampere.

Under reverse bias, $V \leq -V_t$:

$$I_d \approx -I_0$$

As shown in Figure 3-5, this leads to a constant current (typically negligible and less than one microampere) in the reverse direction under reverse bias.

Under forward bias, i.e. $V \geq V_t$:

$$I_d \approx I_0\, e^{V/Vt}$$

As shown in Figure 3-6, this leads to an exponential I-V curve under forward bias. Keep in mind that the slope of a device's I-V curve is indicative of its resistance. In fact, the reciprocal of the slope at a given point is its resistance at that point! Note that at low forward bias voltages, the slope is small, so the diode is operating in a region of high resistance. In contrast, at high forward bias voltages, the slope is large, so the diode is operating in region of low resistance. A forward-biased diode's transition from its high resistance region to its low resistance region occurs around 0.5~0.7 Volts and is known as a diode's turn-on voltage.

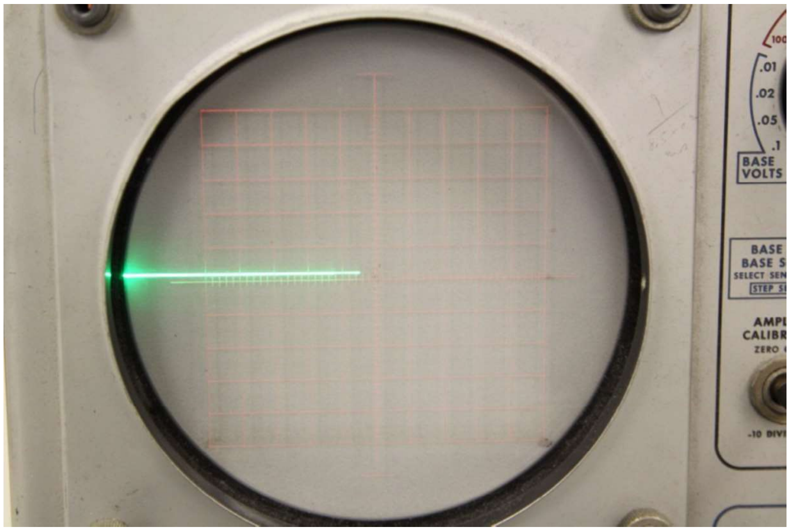


FIGURE 3-5: Diode Reverse Bias Characteristic

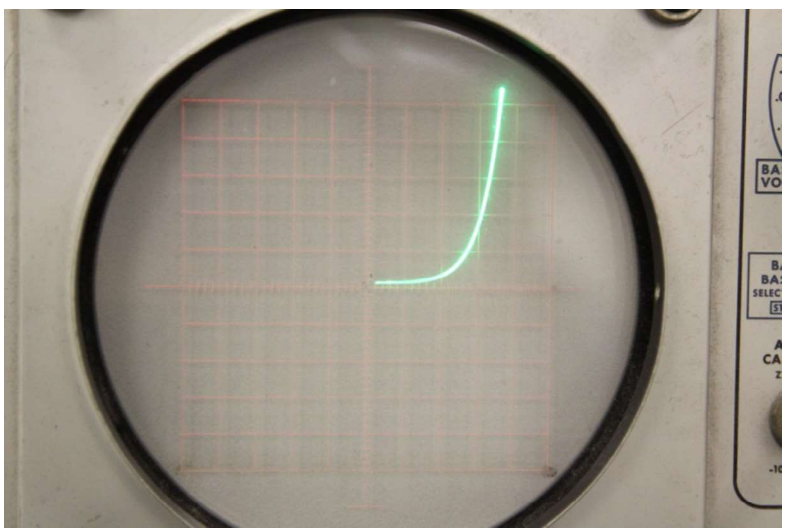


FIGURE 3-6: Diode Forward Bias Characteristic

Note that the power dissipation can be large under reverse bias because the voltage across the device can be quite large (tens of volts) even though the current is small. Under forward bias, the typical voltage is in the order of a fraction of a volt for silicon devices.

To observe the characteristics of diodes, we will be experimenting with light-emitting diodes, also known as LEDs. When a large enough current passes through an LED in the forward direction, the LED will generate light.

There are two ways to tell which side of the LED is the anode and which is the cathode. This is shown in Figure 3-7 below.

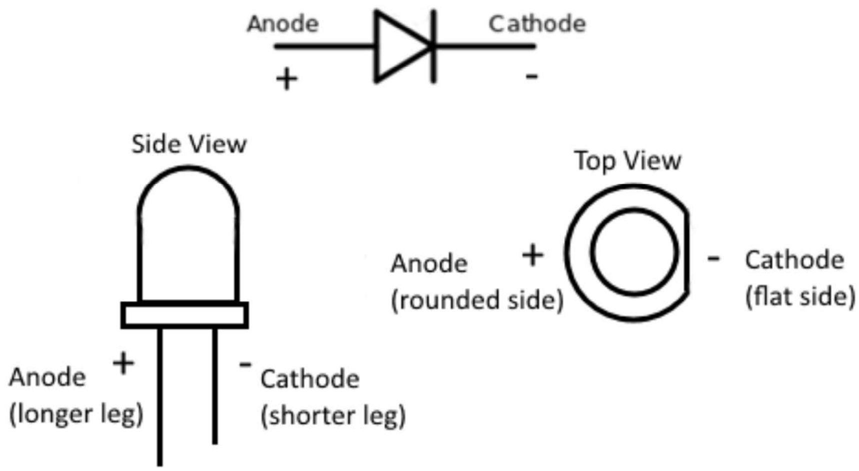
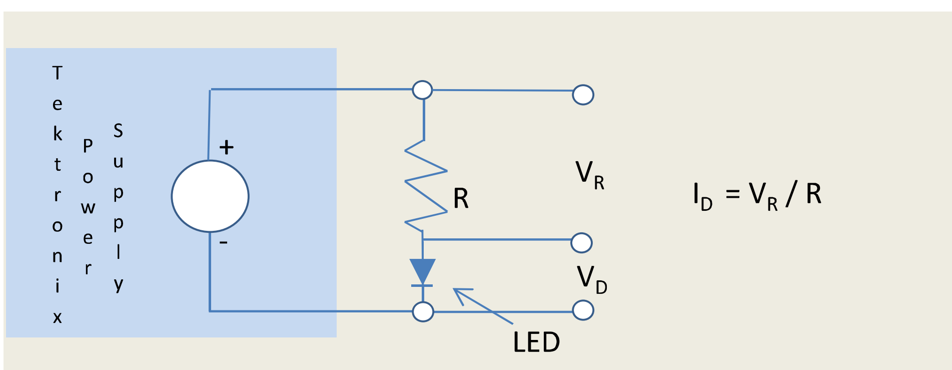


FIGURE 3-7: Physical Diode

NOTE: It is often times unreliable to determine polarity via leg length since component legs can be clipped or twisted. Also, in some IR LEDs, the shorter leg is the anode, but the flat is on the cathode side. Determining which sides are rounded and flat, or using the transistor curve tracer, is more reliable.

To test the current-voltage relationship of diodes, we will employ a **red** LED which can typically stand up to 20 milliamperes. Set up the circuit as below. **We will not reverse bias the LED, as this may break it!**



The 0-20 volts Tektronix power supply should be connected to the LED under test through a 1000 ohm resistor. Thereby, only a maximum of 20 volt/1K-ohm, i.e. 20 milliamperes can flow.

Using a DMM, measure the voltage across the resistor and the voltage across the LED at given power supply voltages. This allows the measurement of the current through the resistor via Ohm's Law. (Note: the potential across the 1K-ohm resistor = 1000 * I_{device}.) Because this is a series circuit, the current through the resistor is the same as that through the LED.

The setup is shown in the Figures 3-8 and 3-9 below:

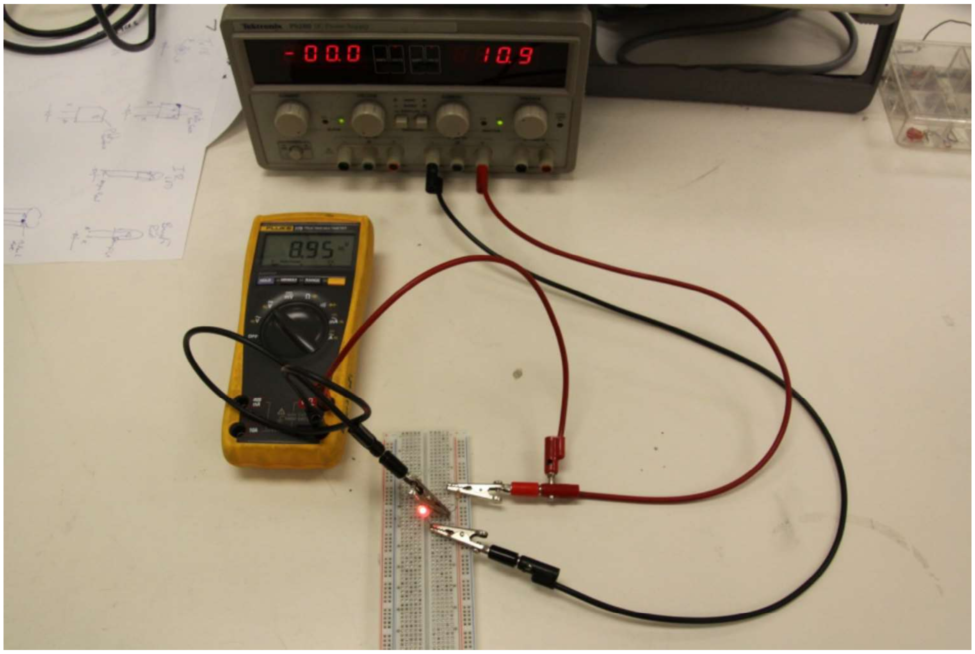


FIGURE 3-8: I VS. V MEASUREMENT SET-UP

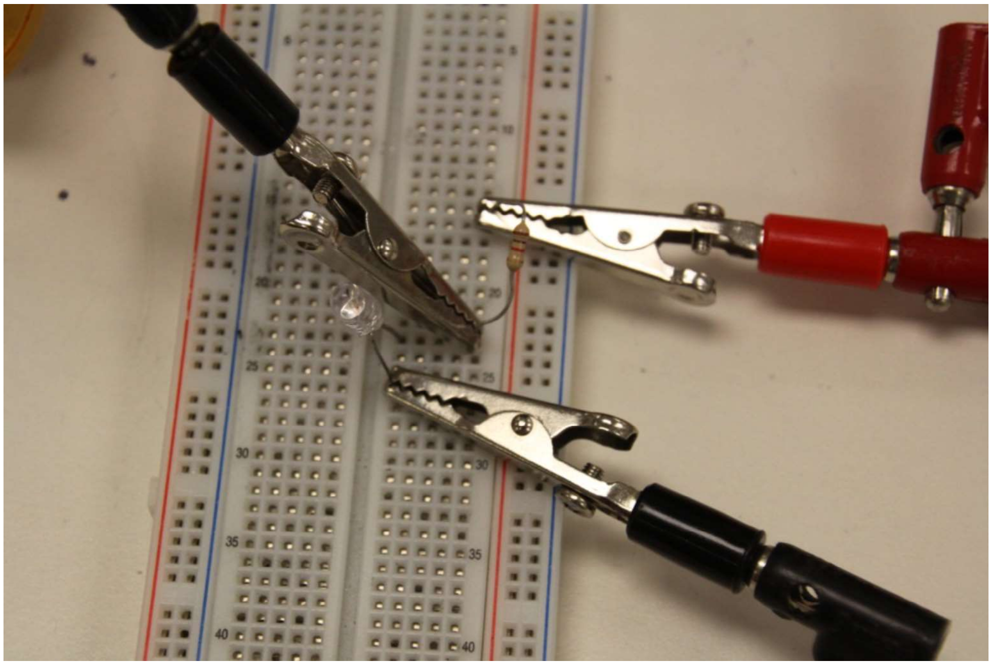


FIGURE 3-9: CLOSE-UP SHOWING LED AND SERIES RESISTOR

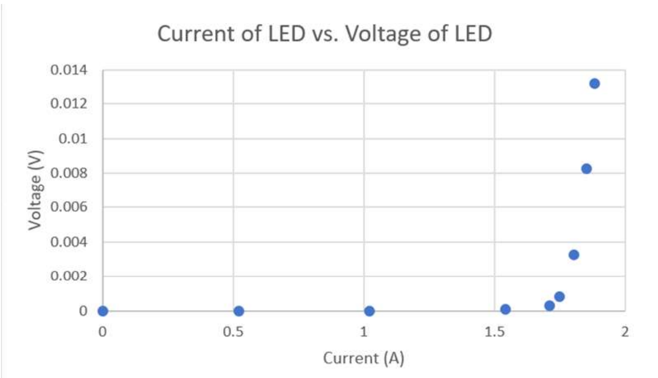
WORK SHEET HERE:

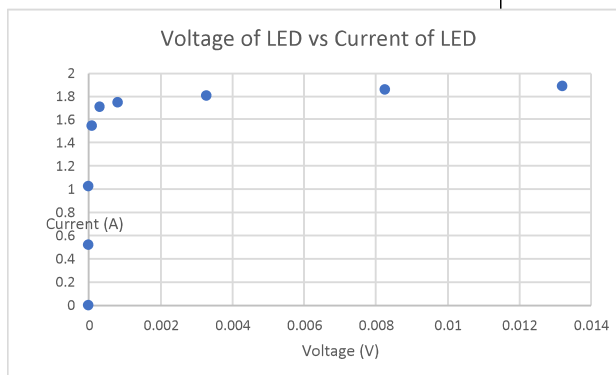
Supply Voltage	$Voltage_{Resistor}$	$Voltage_{LED}$	$Current_{LED}$ ($V_{resistor}$ / 1000)
0 V	0	0	0
0.5 V	0	0.520	0
1.0 V	0	1.02	0
1.5 V	0.08	1.543	0.00008
2.0 V	0.307	1.711	0.000307
2.5 V	0.819	1.747	0.000819
5.0 V	3.275	1.804	0.003275
10 V	8.26	1.853	0.00826
15 V	13.2	1.883	0.0132

At approximately what LED voltage does the LED turn "bright"? Around 6 volts; this was hard to determine though, because the definition for "bright" is somewhat vague. Around 6 volts, the LED shone very intensely, and grew marginally brighter with voltage increases.

Plot the current vs. voltage of the device in the given space below.

ANSWER HERE Assuming "the device" is the LED light:





Phototransistors

In order to understand how phototransistors work, we will first look at a regular transistor. Transistors are three terminal devices that act as linear amplifiers, or, on a basic level, as switches. In this class, we will primarily be working with Bipolar Junction Transistors, or BJTs, shown in the figure below. BJTs have three terminals labeled base (B), collector (C), and emitter (E). The direction of the arrow points in the direction of current flow. (The symbol and operation listed in Figure 3-10 is for an NPN BJT. You may work with PNP BJTs later for your project, which have a different symbol and operation.)

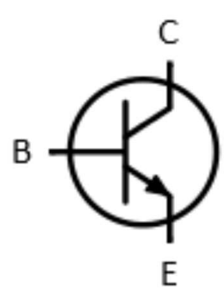


FIGURE 3-10: NPN BJT Symbol

In an NPN BJT, when a high voltage with respect to the emitter is applied to the base, current is allowed to flow from the collector to the emitter. When a low voltage with respect to the emitter is applied to the base, current is no longer allowed to flow from the collector to the emitter. This allows the transistor to act as an electrically controlled switch.

In this portion of the lab, we will work with BJT-based phototransistors. BJT-based phototransistors have an *exposed base* that is sensitive to light. When light shines on the base, the phototransistor allows current to flow from the collector to the emitter.

The visible light phototransistors we use are very similar in appearance to LEDs, shown in Figure 3-11, but have a flat top instead. Note the terminals specified in Figure 3-12.

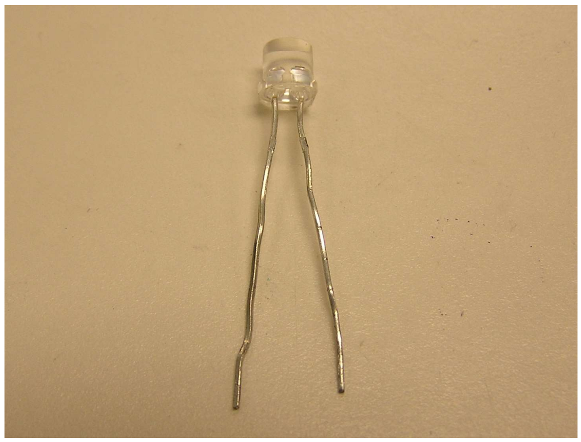
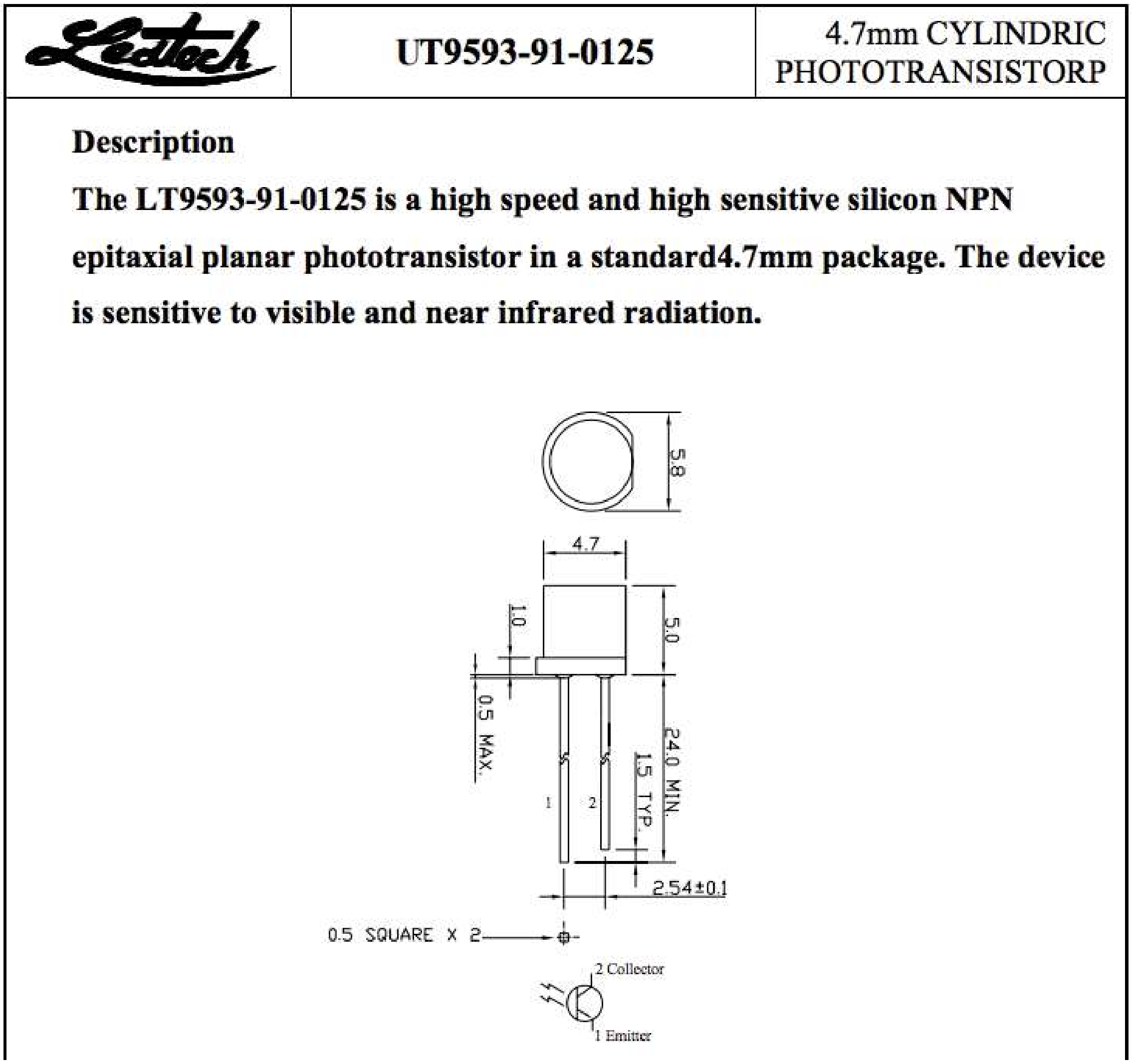


FIGURE 3-11: Visible Light Phototransistor



	UT9593-91-0125	4.7mm CYLINDRIC PHOTOTRANSISTORP

Description

The LT9593-91-0125 is a high speed and high sensitive silicon NPN epitaxial planar phototransistor in a standard4.7mm package. The device is sensitive to visible and near infrared radiation.

FIGURE 3-12: Phototransistor Symbol

Set up the circuit measurement as shown in Figure 3-13 and Figure 3-14. Note that the left-hand side of Figure 3-13 is identical to the circuit from the previous part.

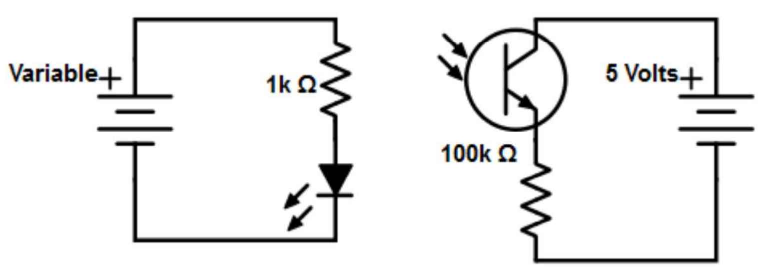


FIGURE 3-13: PHOTOTRANSISTOR EXPERIMENT SCHEMATIC

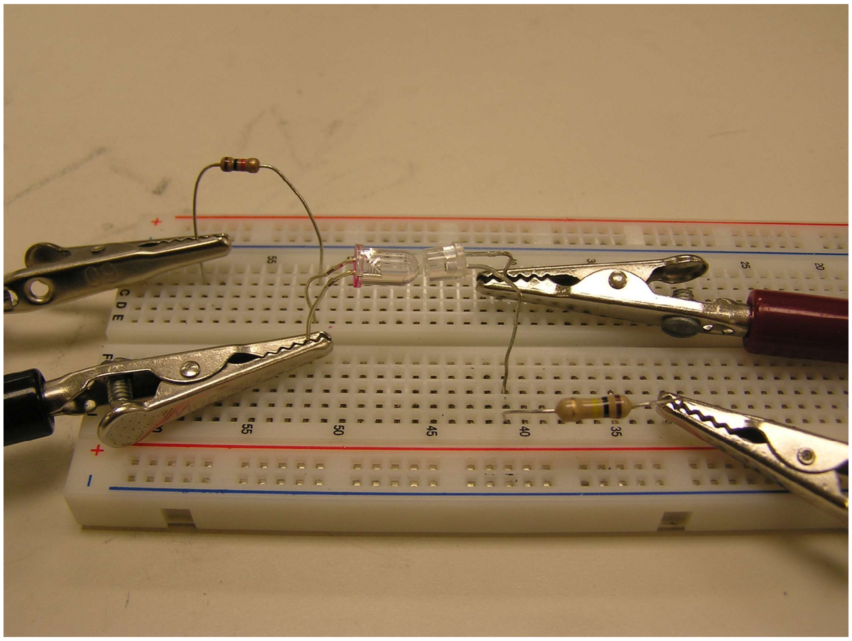


FIGURE 3-14a: PHOTOTRANSISTOR MEASUREMENT SET-UP (LED OFF)

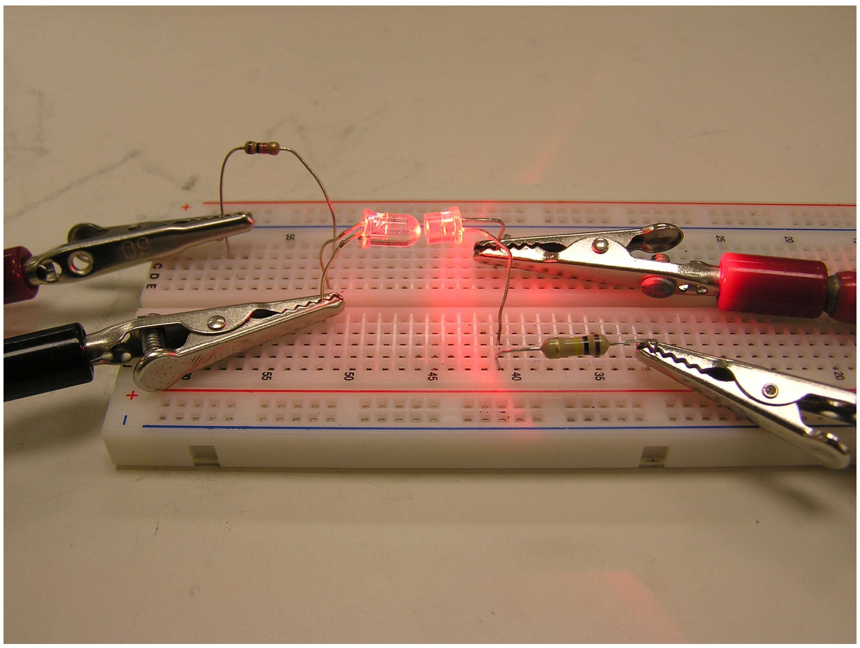


FIGURE 3-14b: PHOTOTRANSISTOR MEASUREMENT SET-UP (LED ON)

Keep in mind that the phototransistor is very sensitive to how directly and closely the LED is pointing at it. You may have to position the LED very close to the phototransistor to get appreciable results.

Measure the voltage across the 100 kΩ resistor when the LED is off. Turn the variable supply voltage to 15 Volts and measure the voltage across the 100 kΩ resistor again.

WORK SHEET HERE: (Use DMM for your voltage measurements only!)

We used an infrared diode and phototransistor:

	Voltage$_{100\ k\Omega}$	Calculated Current$_{100\ k\Omega}$
White strip ~~LED off~~	4.8	0.000048
Black strip ~~LED on~~	2.6	0.000026

How well does your phototransistor act as a switch? (Ask your TA or mentors for help if you are experiencing difficulty in getting the setup to work)

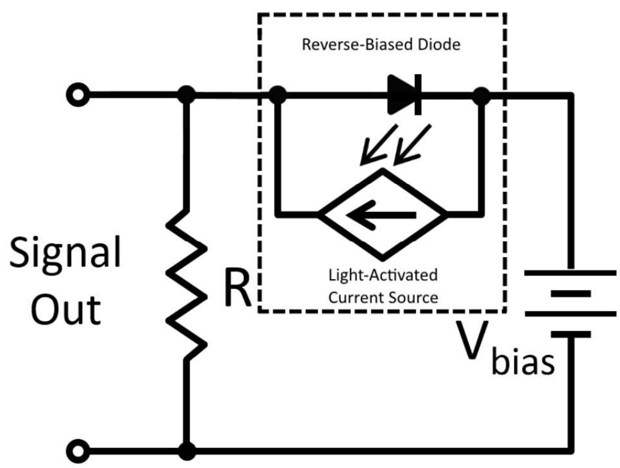
Our phototransistor works well as a switch - when there is a not much infrared radiation (i.e. when the black strip is absorbing most of the radiation), the phototransistor does not let much current through. When there is a lot more radiation, the transistor allows more current to pass through.

Photodiodes

The operation of photodiodes is a fairly complex topic matter that you will study more deeply in later classes. As such, we use models in this section to make the information more digestible than it would otherwise be.

Photodiodes are light detection devices designed for high sensitivity and low noise with small areas on the order of 10^{-8} to 10^{-6} cm^2. Care must be taken not to injure these devices.

To understand how photodiodes work, let us take a look at the following circuit.



For the purposes of this class, photodiodes are modeled as a current source in parallel with a diode, as shown in within the dashed box.

When no light is shining on the photodiode, the light-activated current source is off. In this case, the circuit can be reduced to a voltage source in series with a reverse biased diode and resistor. As we know from before, reverse-biased diodes allow a current of $I_d \approx -I_0 \approx 0$ to pass in the reverse direction. Therefore, no current passes through the circuit and there is a corresponding Signal Out voltage of 0 across the resistor.

When light is shining on the photodiode, then a current I_{gen}, which varies with light intensity, is generated by the light-activated current source. We choose a V_{bias} such that $V_{bias} > I_{gen}R$, which will maintain the diode in reverse bias (remember that a diode is reverse biased when the anode is at a lower potential than the cathode). Therefore, the only current passing through the circuit is the generated current I_{gen}, and there is a corresponding Signal Out voltage of $I_{gen}R$.

A simplified model for the photodiode is shown again in Figure 3-15:

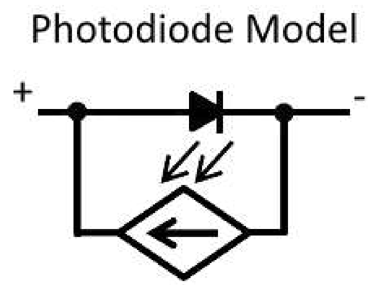


FIGURE 3-15: Photodiode Model

On circuit diagrams, photodiodes are represented by light shining onto a diode. The current source, as is present in our photodiode model, is not shown in the schematic symbol. Note that the location of the anode and cathode in our model and schematic symbol is still the same. We will continue using the model, which will be shown inside a dashed box, in this section of the lab for analyzing photodiode operation.

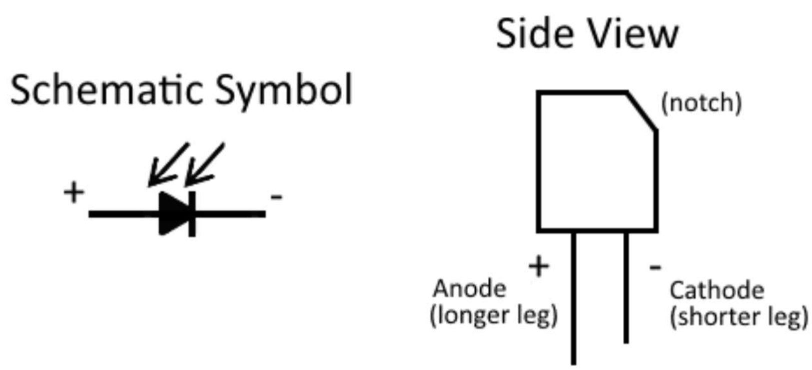


FIGURE 3-16: Photodiode Symbol

The side-look IR photodiodes we will be using in this lab are shown below in Figure 3-17.

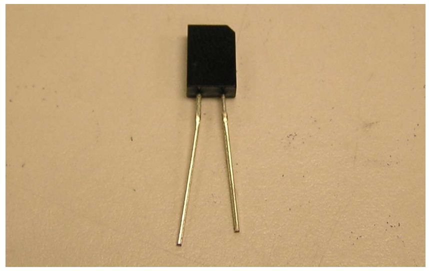
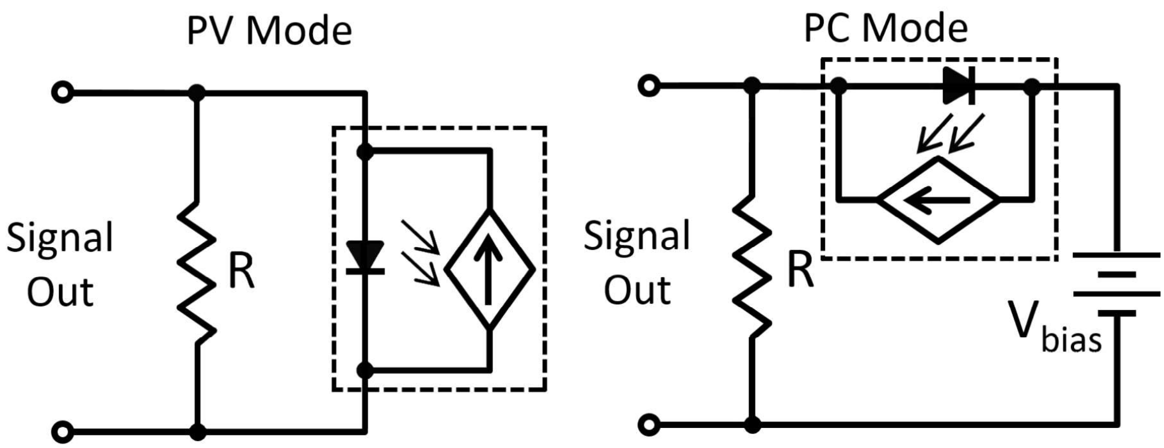


FIGURE 3-17: Side-look IR Photodiode

There are two common photodiode circuits: photovoltaic (PV) and photoconductive (PC) mode. The operation of PC mode has already been discussed in the introduction of photodiode operation.



Unlike PC mode, PV mode lacks a biasing voltage source and consequently operates differently. We will once again consider our photodiode model of a diode in parallel with a current source.

In PV mode, a non-illuminated photodiode will not generate a current and so there will be 0 voltage at the Signal Out. An illuminated photodiode will have a generated current I_{gen} from its light-activated current source, which then passes through the resistor to create a corresponding Signal Out voltage of $I_{gen}R$. In PV mode, we typically operate the diode sub-component in a high resistance region (the voltage across the diode, $I_{gen}R$, is low) so that the current through the diode sub-component I_d is negligible compared to I_{gen}.

Recall that in the LED section, we defined a positive current as current flowing into the anode. In both PV and PC mode, current generated by the light-activated current source will leave the anode of the photodiode, resulting in negative current.

In PV mode, the anode is positive with respect to the cathode due to the voltage drop across the resistor. By the Passive Sign Convention, a negative current and positive voltage give us negative power—the photodiode provides power in PV mode.

Remember that for PC mode, we choose a V_{bias} such that $V_{bias} > I_{gen}R$ so that the photodiode remains in reverse bias, where the anode is negative with respect to the cathode. By the Passive Sign Convention, a negative current and a negative voltage result in positive power—the photodiode consumes power in PC mode. It is straightforward to see that V_{bias} provides power to the photodiode and resistor.

In summary, power is provided by the photodiode and absorbed by the resistor in PV mode while power is provided by the biasing voltage source and absorbed by the photodiode and resistor in PC mode.

Please request the assistance of your TA or mentor to observe the photodiode illuminated characteristic on a curve tracer, shown in Figure 3-18. Note that in Quadrant IV, the photodiode exhibits a positive voltage drop and negative current, which corresponds to PV mode. In Quadrant III, the photodiode exhibits a negative voltage drop and a negative current, which corresponds to PC mode.

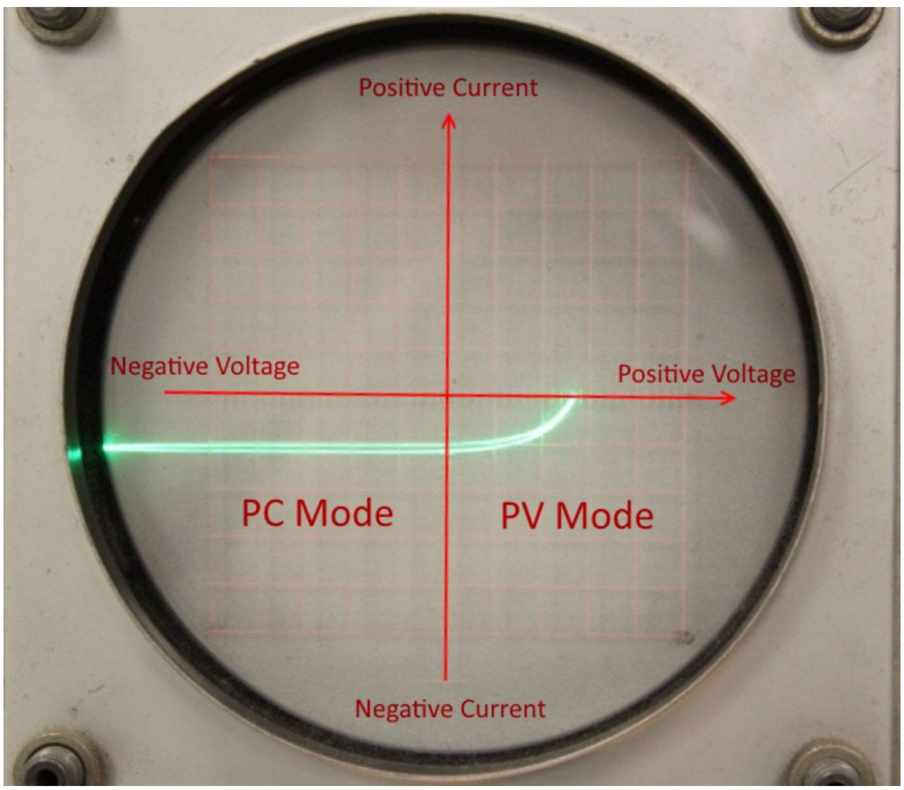
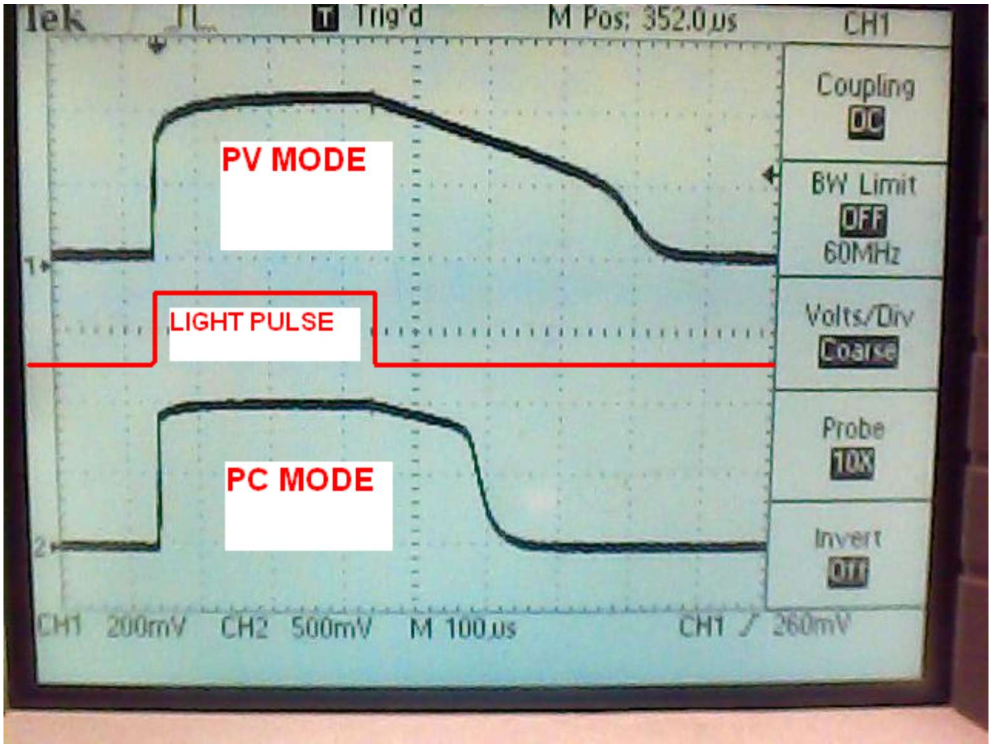


FIGURE 3-18: Photodiode Illuminated Characteristic

PV mode is suitable for power generation such as in solar cells since the power being provided in PV mode comes solely from light. While PC mode is not suitable for power generation since it requires a biasing voltage source to provide power to the circuit, PC mode responds faster to changes in light and has a higher signal to noise ratio (SNR) as shown in the oscilloscope reading below.



What are the advantages of each circuit? Briefly explain.

ANSWER HERE:

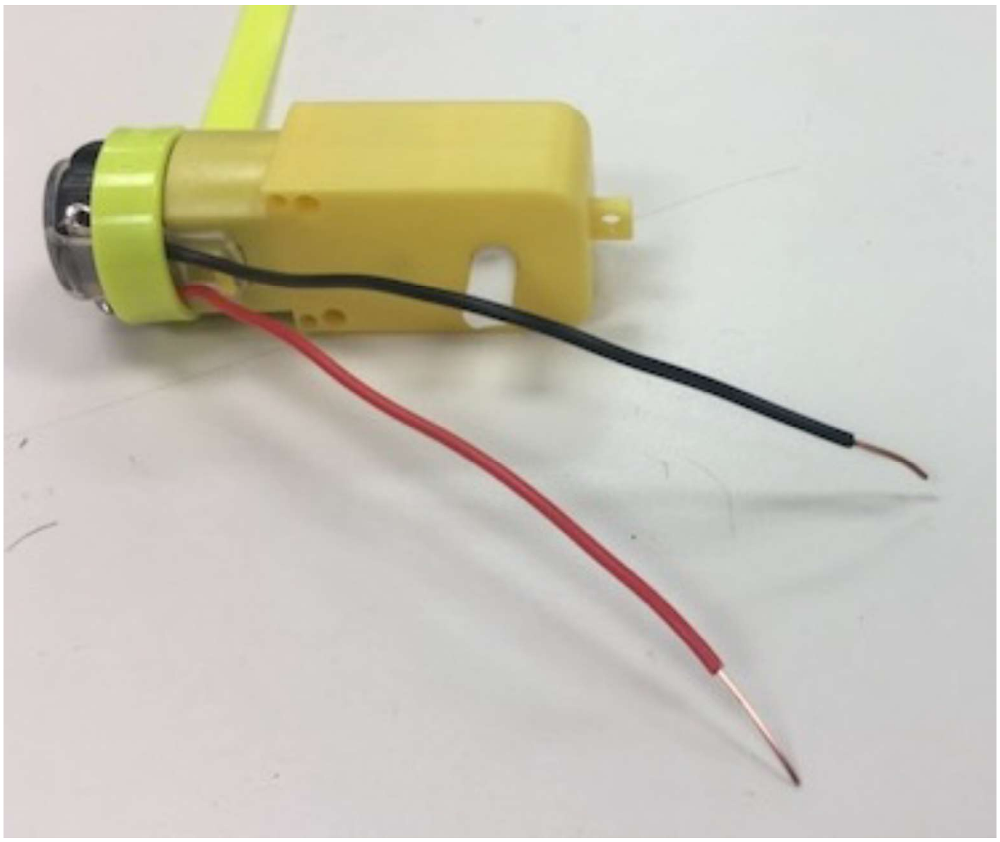
PC circuits respond more quickly to changes in light and have a higher signal to noise ratio, meaning that the readings are less likely to be distorted. While PV circuits do take longer to respond to light and are not as clear as PC circuits, they are better for power generation, because the power provided in PV circuits is just from light itself, while PC circuits need a biasing voltage source.

Electro-Mechanical Transducers

Motors and Generators

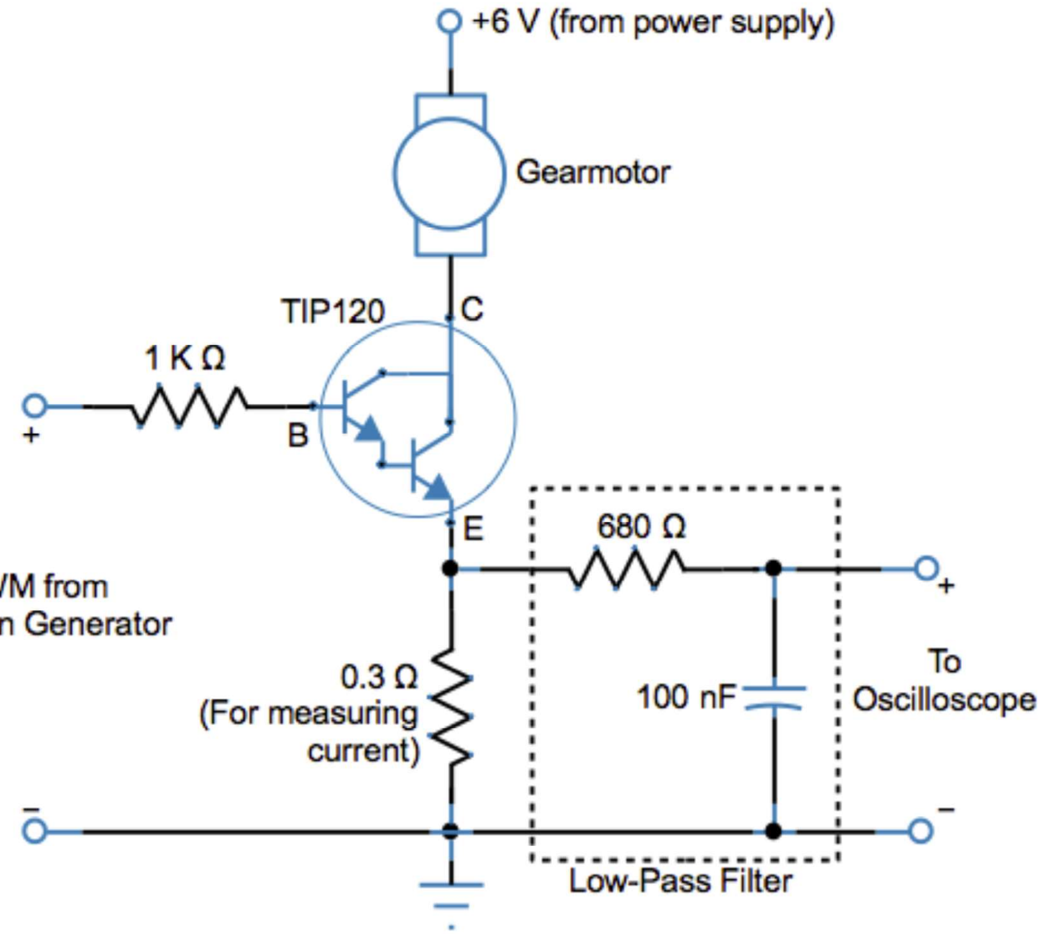
In this section, you will create a circuit that controls the speed of the electrical motor that is in the car that is part of the EE3 project. You will learn that an Arduino microcontroller PWM output pin can control a single TIP120 NPN (Darlington) transistor that will drive the motor. The duty cycle of the PWM signal controls the motor speed.

You will be supplied a copy of the DC gearmotor that is used in the project.



Look up the data sheet for the TIP120 Darlington transistor (google “TIP120 datasheet”). Determine which pin is associated with the emitter, base, and collector.

Hook up the circuit shown below (Do NOT connect the power supply yet):



NOTE: We will measure current <u>indirectly</u> by measuring the voltage across the <u>filtered</u> 0.3 Ω resistor. You will NOT use the 0.3 Ω resistor in your project.

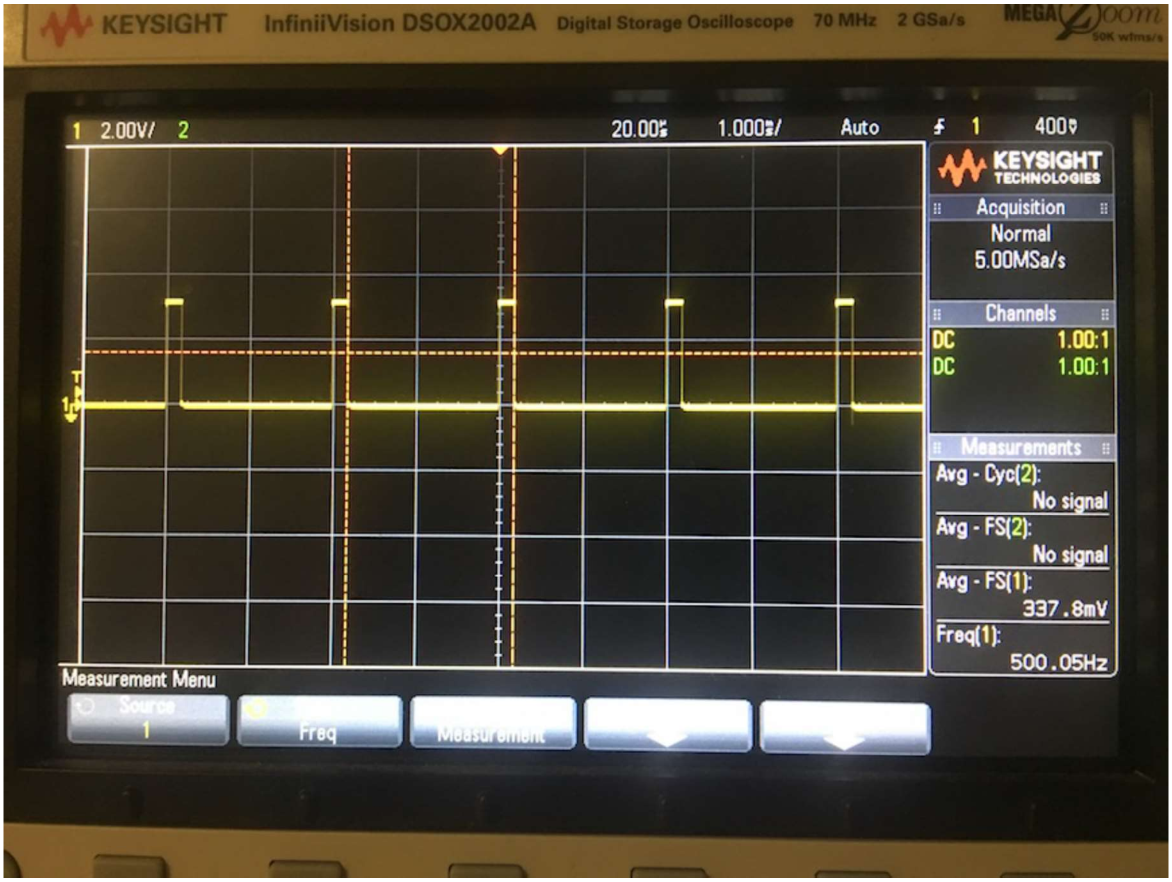
1. The power supply will connect 6 V to the circuit, and provide the current to drive the motor.
2. Set the function generator to provide a pulse train at 500 Hz and switch between 0 V and 3.3 V (this is similar to the PWM signal from the Arduino Nano).


RIGOL DG1022
2 Channel
Function/Arbitrary Waveform Generator
20MHz
100MSa/s
Pulse
High Z
CH1
500.000,00 Hz
Freq
Ampl
Offset
DtyCyc
Delay
AligPha
Tektronix PS280 DC Power Supply


RIGOL DG1022
2 Channel
Function/Arbitrary Waveform Generator
20MHz
100MSa/s
Pulse
High Z
CH1
3.300 VPP
Freq
Ampl
Offset
DtyCyc
Delay
AligPha
Tektronix PS280 DC Power Supply

.

3. Set the pulse train (use the **<u>Pulse</u>** button; see above picture) duty cycle to 10%.
4. Connect the + and − leads of the function generator to the yellow Channel 1 on the oscilloscope. Adjust the oscilloscope settings to show the PWM signal and confirm that the function generator is correctly set.
5. Make sure that 5 pulses are shown on the oscilloscope screen. Adjust the oscilloscope settings (MEAS button) to show the average voltage from the function generator.



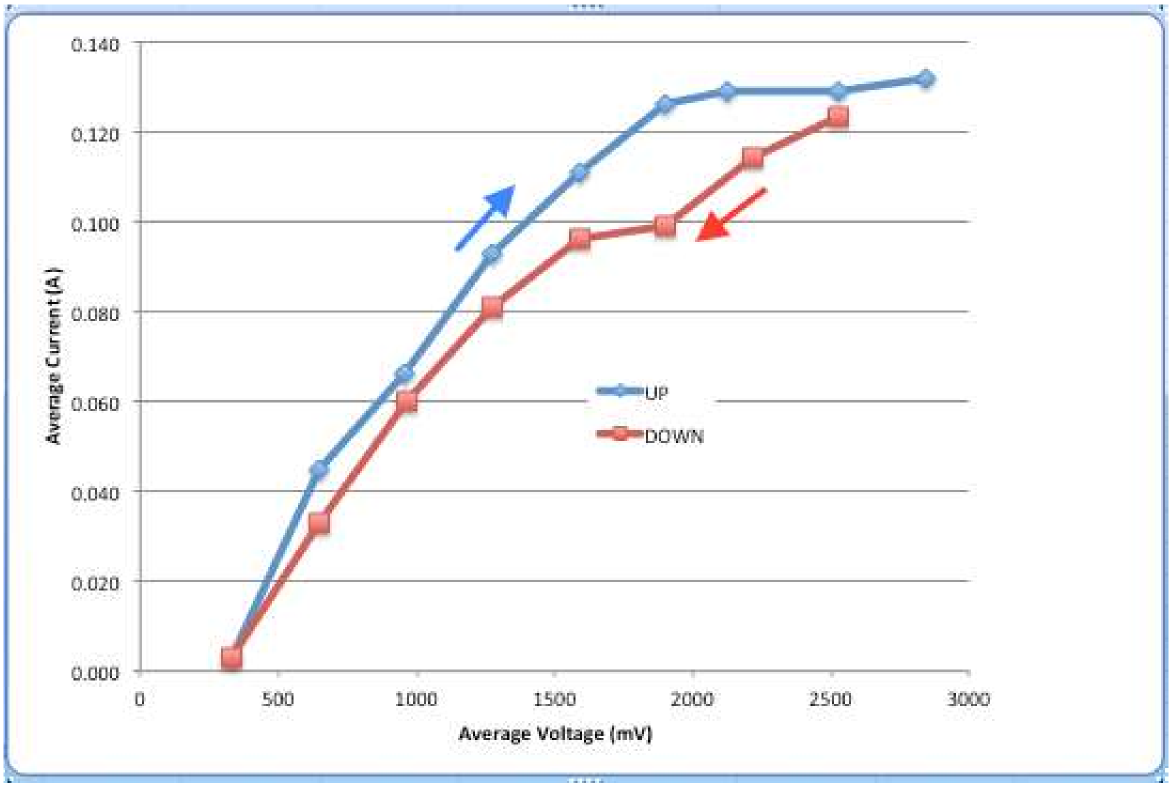
6. Connect the oscilloscope (green) Channel 2 + lead to the top of the 0.3 ohm resistor. Adjust the oscilloscope settings (MEAS button) to measure the average value (FS) of the Channel 2 signal.
7. Connect the power supply to the circuit. The motor should not turn.
8. Increase the duty cycle by 10% increments up to 90%. The motor should start to turn at around 30% duty cycle, and turn faster with increasing duty cycle. At 50% duty cycle, your oscilloscope screen should look something like the picture below.

9. Now decrease the duty cycle by 10% increments back down to 10%. The motor may stop turning at a different duty cycle from that where it started turning on the way up.
10. At each duty cycle setting, record on the work sheet below the average voltages for both channels indicated on the oscilloscope screen.

WORK SHEET HERE:

Duty Cycle %	Average Motor Volts	Average 0.3 Ω MilliVolts
20	0.5826	18.96
30	0.8811	25.86
40	1.1673	29.64
50	1.4583	31.34
60	1.7500	34.21
70	2.039	34.11
80	2.3761	33.95
90	2.6175	34.61
80	2.3371	33.28
70	2.1770	30.41
60	1.8648	30.54
50	1.5556	29.67
40	1.2458	27.15
30	0.9337	23.01
20	0.6248	16.95
10	0.3112	3.88

Enter your data into Excel. Create another column where you compute the motor current using Ohm's law, and plot your results (current vs. voltage). You should get something like this:



What voltage and current are required to just start the motor spinning? Voltage = 0.811 Volts
Current = 0.02586 Amps

Week 3 Lab End