Experiment 8: Semiconductor Devices

Name/NetID:

Teammate/NetID:

Section AB/BB:

0 1 2 3 4 5 6 7

8 9 A B C D E F

(circle one)

Laboratory Outline

In today's experiment you will be learning to use the basic building blocks that drove the ability to miniaturize circuits to the point that now you have a computer inside a small mobile device that has more computing power than the flight computers inside the early space-flight missions – the diode and transistor. The miniaturization was achieved through the use of semiconducting material whose conductivity could be varied easily at a very small scale. Because the behavior of both are both notoriously *non*linear, we will first focus on characterizing these new devices and next week we'll apply them as a key feature in motor-speed control. Throughout this experiment, we'll employ simple models of both the transistor and the diode. It is important to realize that in circuit analysis we employ idealized models of every device and the choice of each model represents a tradeoff between utility and accuracy.

Learning Objectives

- Measure, analyze, and model the IV characteristics of the diode.
- Characterize the motor using a BJT-based motor-drive circuit.
- Recognize the efficiencies of using this design over that of voltage-divider-based motor control.

Modelling Diodes:

The diode can be thought of a one-way valve that only allows current to flow in one direction. With this capability we can build circuits that regulate voltage or protect devices from being powered incorrectly. In this lab we'll examine what this behavior means in terms of the IV characteristics of the device. In addition, we'll develop a *linearized* model of the diode in the same way we did for the motor last week.

Building Circuit with Transistors:

The transistor is a *three* terminal device that can be thought of as an electrically-controlled switch. In today's experiment, you'll learn to construct simple circuits that employ the transistor as a switch for controlling the current flow through a branch of a circuit.

Notes:

Diodes

Like many devices, the diode is best characterized by the voltage current relationship of the device. In previous labs, we examined the IV curves of resistors and motors. Today, we'll examine the IV curve of a diode and use that to develop some intuition on how diodes behave.

Before we characterize the device, let's take a moment to look at the symbol, device packaging and some basic terminology so that we minimize confusion. Think of the symbol as an arrow that indicates which direction it will allow current to flow (current flows from anode to cathode). Basic diodes have two states in which they operate. The diode is referred to as being **ON** when *current is flowing through the device*. The diode is referred to as being **OFF** when *current is not allowed to flow*. Each diode has a **turn-on voltage** which *indicates the minimum voltage necessary to turn the diode ON*.

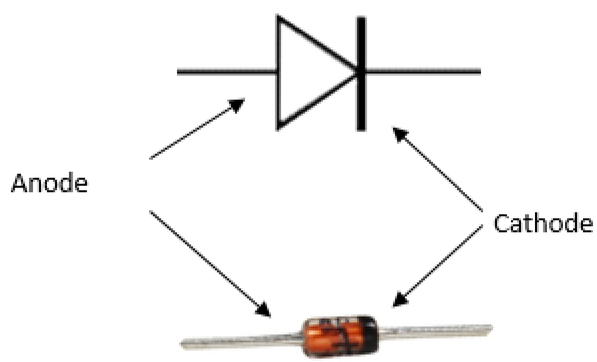

Figure 1: Anode and cathode of a diode

Now, let's analyze the behavior of a diode within a very simple circuit.

- ✓ Construct the circuit shown in the 2 using the DC power supply as the voltage source.
- ✓ Setup both DMMs to measure the voltage across the diode and current through the diode simultaneously.

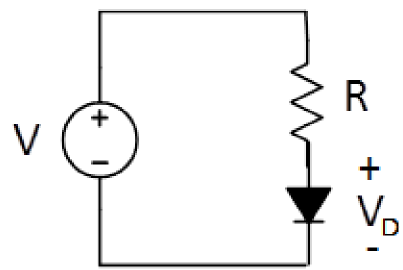

Figure 2: Simple circuit for collecting IV characteristics of a diode.

R is a current-limiting resistor, typically around $330\ \Omega$. The voltage source is a DC power supply.

Question 1: Sweep the voltage of the power supply from 0V to 6V and collect the voltage across the diode and current through the diode. **Idea**: Instead of using an ammeter, you can record the voltage across the resistor as well as the diode voltage and compute current using Ohm's Law.

Voltage	Current	Notes

Table 1: IV data for a diode, forward biased.

Notes:

Notes:

Question 2: Now take a single measurement at $V = -3V$. (You can do this by reversing the polarity of the power supply.) Make sure to label your voltage as negative in the table!

Voltage	Current	Notes

Table 2: IV data for a diode, reverse biased with $V = -3\ V$.

Question 3: Plot your diode data in MATLAB as a single curve.

Question 4: Perform a linear curve fit on the region in which the diode is ON. Estimate the voltage at which the diode turns ON.

Question 5: Using the linear curve-fit, determine the Thevenin equivalent circuit of a diode when it is ON.

Transistors

The advantage of using diodes in a circuit is that it allows us to control the direction of current flow through the circuit. Transistors give us even greater control over current flow through the circuit. As with the diode, the pins on the transistor serve specific functions and correspond to specific nodes on the schematic symbol. A quick reference is shown below to help with wiring up your transistor circuit.

Notes:

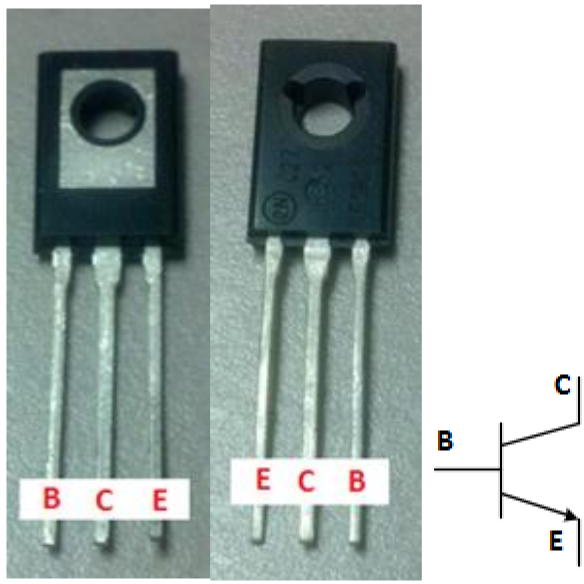

Figure 4: Pinout of the transistor used in ECE110 lab.

In general, the transistor symbol is drawn without the letters B, C and E explicitly written on each of the nodes. Instead, an arrow is drawn coming out of the emitter (as shown) leaving the Collector and Base easily distinguishable. It should also be noted that for the purposes of this course, the arrow on the transistor indicates the direction in which current flows through the device.

Modelling the Transistor as a Switch

The transistor can be modeled as a simple voltage controlled switch where the Base of the transistor is the input and the Collector to Emitter "connection" is either an open circuit or a closed circuit. Notionally, when the input is 0 V the switch is OFF and current is not allowed to flow through the device. When the input is 5 V, the switch is ON and current is allowed to flow. With that in mind, let's construct the following circuit where a transistor is used to control the current flowing from a battery through a 10 kΩ resistor.

While this notional description of the transistor is helpful for gaining some intuition about the circuit, the transistor itself is commonly considered be controlled by current flow. This is why we have a 330Ω resistor from the power supply to the base to limit the current flow into the input.

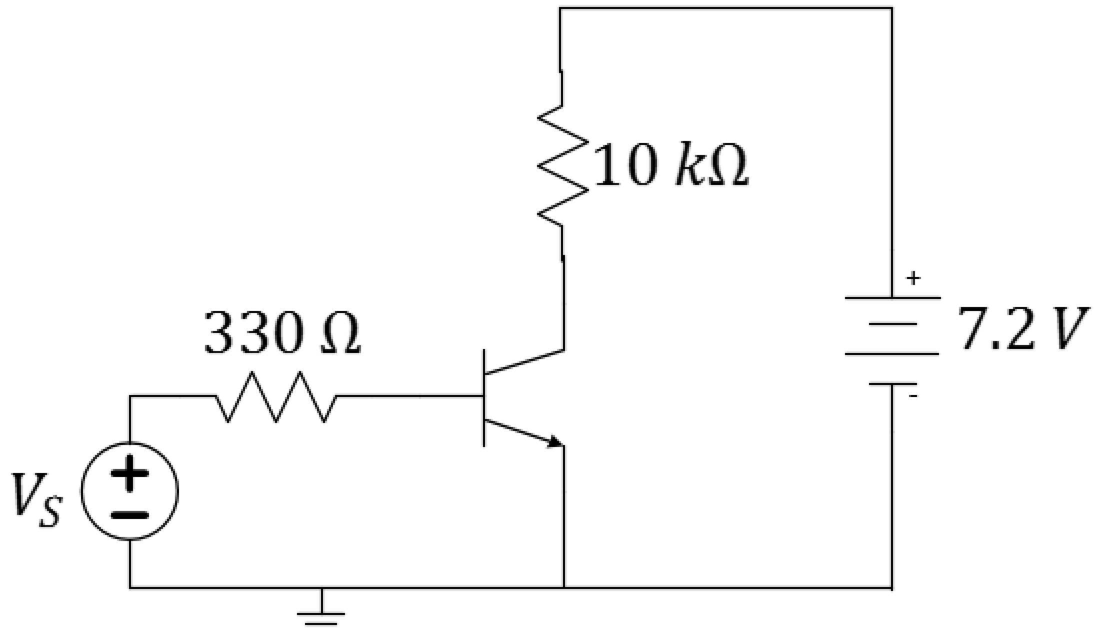

Figure 5: Simple circuit for collecting IV characteristics of a transistor.

Question 6: Sweep the voltage of the power supply from 0V to 6V and record several data points of the voltage across the 10 kΩ resistor and the corresponding voltage across the collect/emitter. Place these values in your own table in the Notes space.

Question 7: Plot the voltage across the $10\ k\Omega$ resistor as a function of the input voltage. Indicate the region of input voltages over which the switch changes from open to closed.

Question 8: Is a voltage-controlled switch a reasonable approximation for this transistor? Explain your reasoning.

Notes:

The real advantage of using the transistor in this manner is that we can now use circuitry powered by one voltage source to control circuitry powered by a secondary voltage source. Traditionally, this type of circuit is called an amplifier circuit because we can use a small power input to control a much larger power source.

As you may have seen from your own experimenting, the output pins on the Arduino have a hard time powering our DC motors. By replacing the 10k resistor (in the above circuit) with a motor, we can control the motor while allowing it to draw current directly from the battery.

Driving a Motor

The circuit shown below is basic motor drive circuit that we will use for the remainder of this semester. As you can see, this circuit makes use of both a transistor and diode to drive the motor. As hinted in the previous section, the transistor is used to switch the motor on and off. In addition, we've added a diode in parallel with the motor to protect our circuitry from any spurious voltage spikes generated by the motor.

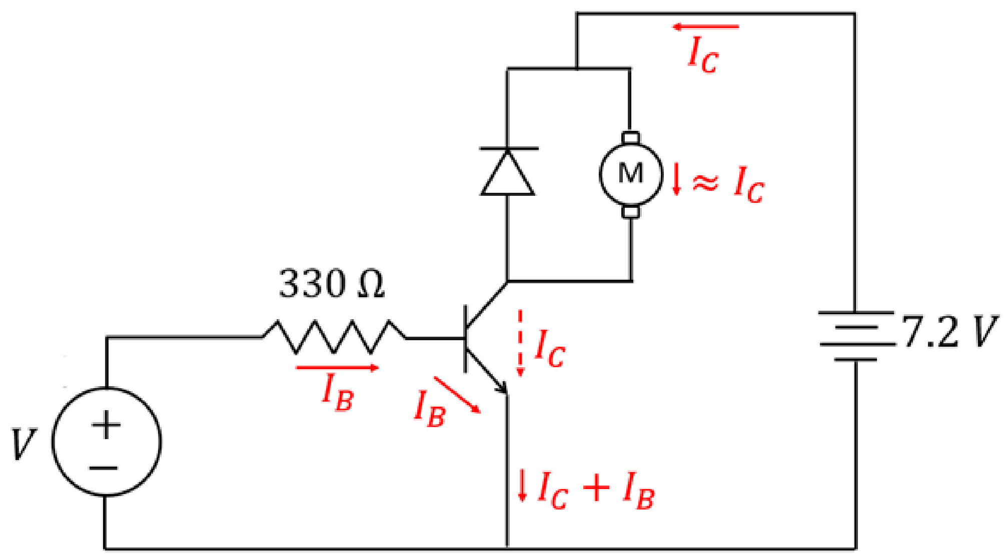

Figure 6: Circuit schematic of the motor drive circuit.

Construct the motor drive circuit detailed in Figure 6 using the DC power supply as the input voltage and the NiMH battery as the 7.2V source. Add an ammeter to measure I_C.

Notes:

Question 9: Sweep the DC power supply V_{in} from 0 V to 6 V and measure both the voltage across the motor V_m and I_C. *You will need this data for next week's lab, so you should photo, copy, or type it into MATLAB to have it as a reference in case this lab is not graded and returned in time.*

			Comments:

Table 3: Motor-drive circuit Characteristics

Notes:

Question 10: Record the turn-on voltage V_{in} and corresponding collector current I_C here.

Question 11: At what input voltage does the motor hit its maximum speed? (When does the motor speed stop increasing?) **NOTE**: This happens due to an effect of the transistor circuit called “saturation”.

Question 12: Starting from 5V, slowly turn down the input voltage V_{in} until the motor stalls. Record the voltage.

Question 13: Set the DC power supply to 5V and measure the total current sourced by the power supply as well as the voltage drop across the motor. Compute the efficiency of the circuit…the ratio of the power absorbed by the motor divided by the total power delivered by the battery.

In next week’s experiment, we’ll explore a method of controlling motor speed that requires this circuit. **Leave this circuit assembled on your breadboard** so you won’t need to rebuild it next week.

Notes:

Conclusion

Question 14: Briefly discuss the process of modelling the diode and the advantages or disadvantages of the model you developed.

Question 15: Explain how the transistor aids in driving a motor. In your explanation, explain what would happen if the transistor was not involved.

While the models we used for diodes and transistors are highly simplified, they still have a great deal of utility. In particular, these devices give us control over the current flow through the branches of a circuit. This is particularly useful when we want to control the current through a motor using a controller that can't handle a great deal of current itself. Next week, we'll gather some of the final pieces of the puzzle necessary for building a power-efficient autonomous car.

What You Learned

After today's lab, you are able to build circuits involving simple semiconductor devices. You understand the tradeoffs made when modelling semiconductor devices and how those models can be employed in circuit design. Lastly, you can build a high-power circuit necessary for driving a small DC motor via a low-power control signal.

Explore More!

As time permits, please continue your experimentation using the Modules recommended for this week or other modules from previous weeks. Recommended are ***Explore More!*** **Clipping Circuits,** ***Explore More!*** **Arduino-based Wall-Follower,** and ***Explore More!*** **Characterizing Optical Sensors**.

Notes:

Lab Report Rubric

The following rubric will be provided at the end of each lab procedure. As a final step in preparing your lab report, you will use this rubric to analyze your own performance.

Section	**Criterion**	**Comments:**
Experimental Setup and/or Design Description	Circuit Schematics are drawn neatly, accurately, and properly labeled. Decisions regarding experimental setup and design are clearly explained.	
Measurements	Tables include units and proper precision. Any *new device* introduced should be characterized using measurements!	
Computations	Computations performed on raw data are *explicitly* described and follow rules for significant figures.	
Analysis	Graphs have title, labels, units, scale, legend; Lines for curve-fitting appear in the graph when needed and parameters like the intercepts and the slope are labeled.	
Modeling	A mathematical model for the curve-fit graph allows for more abstract references to the device's behavior. The expected behavior is explained in the context of the graph.	
Conclusion	Conclusions are drawn from your experimental results to support the reason(s) for completing the experiment. Closes the loop on the Introduction.	
General Formatting	Answers to questions clearly labeled. The overall appearance of the report is professional.	
Self-assessment	This table has been thoughtfully completed.	