**Transistors:**

*“Any sufficiently advanced technology is indistinguishable from magic.”*

Arthur C. Clarke

We are surrounded by electronic marvels, and most of the “magic” they perform is carried out by transistors. This lab is about the physics of transistors. This may make them appear less magical, but their significance in science and technology cannot be overstated.

Only one person has ever won two Nobel Prizes for physics. It wasn’t Marie Curie (she won one for physics and one for chemistry) and it wasn’t Albert Einstein (he only won one although he deserved more). It was John Bardeen, co-inventor of the transistor. Bardeen is shown on the left in the photo below, along with co-inventors William Shockley and Walter Brattain at Bell Labs in 1948. Shockley ran the lab and the other two worked for him. Coincidentally, transistors have three external wires or leads, and one of those wires gives instructions to the other two wires.



Transistors are circuit elements that can change their behavior depending on their environment. They have three external wires or leads. Two of the leads carry the main electrical current in and out of the resistor. The effective resistance between those two wires changes depending on the electrical environment of the third wire. The third wire acts as sort of a switch, turning the first and second wires on or off based on an external voltage or signal. Depending on the strength of the signal, it can also set the circuit to “only partially on” or “only nearly off” so transistors can be used to make a range of electrical decisions and produce a wide range of effects.

The two wires which carry the main electrical current are either called “emitter and collector” or “source and drain” depending on the type of transistor. Which one we connect to the positive terminal of a battery also depends on the type of transistor, and is indicated in the diagram on the next page. The third wire is the one that collects information and acts like a switch. It is either called the “base” or the “gate” depending on the type of transistor.

Diagrams of four common types of resistor are shown below.

PNP

transistor

NPN

transistor

N-channel

MOSFET

P-channel

MOSFET

+ “emitter”

+ “collector”

- “collector”

- “emitter”

base

base

gate

gate

+ “source”

- “source”

- “drain”

+ “drain”

All four transistors are drawn such that the more positive part of a circuit would be connected to the top wire. The more negative part of a circuit would be connected to the bottom wire so current would flow down through each transistor as shown. The wires leading to the left are the “bases” or “gates” which respond to external voltages (off to the left of these diagrams) by changing the resistance between the other two wires. In this way they turn circuits on or off.

The two transistors at the top of the diagram, PNP and NPN, are the standard low-voltage resistors that fill most electronic gadgets. They can be very small but they usually cannot withstand voltages higher than a volt without burning out. The two transistors on the bottom of the diagram are called MOSFETs or Metal Oxide Silicon Field Effect Transistors. These are generally larger than the other transistors but they can withstand voltages of several volts.

Notice that the bases of the NPN and PNP transistors are drawn as though they are connected to the other leads while the gates of the MOSFETS are not. This is an accurate description. The small current in the base of a PNP or NPN joins the (usually much larger) current in the rest of the circuit. In a MOSFET, however, the “Metal Oxide” forms an insulating barrier so that the rest of the transistor experiences only the electric “Field Effect” from the gate.

The transistors on the left side of the diagram, the PNP and P-channel transistors, turn off and on in the same way. The same signal that turns off a PNP transistor will turn off a P-channel transistor. The same is true for NPN and N-channel transistors, which are turned off and on by signals of opposite sign from the PNP and P-channel transistors. The PNP and NPN transistors turn off and on in the same way as the MOSFET transistors shown below them in the diagram, although the MOSFET transistors can handle a signal of greater voltage.

This idea of a circuit being turned off or on by an external signal may be hard to understand without actually seeing it. This lab is about exactly that.

**Part I: An *electrostatic* signal**

To be clear at the outset, this part of the experiment is about something electrical engineers try *not* to do. Electric circuits are usually designed to be protected from static electric fields. However, a static electric signal is useful for purposes of seeing how transistors operate.

For this experiment you will need MOSFET resistors capable of operating with a gate voltage of several volts. If both are available, use a P-channel and an N-channel MOSFET as shown in the diagram below. If only one is available, build only the left-hand or right-hand part of the circuit. You may have to consult the literature associated with your MOSFETs to determine which lead is the source, the drain, or the gate. The appropriate voltage for the power supply also depends on the specifics of the transistors, so a number of cells such as AA batteries in series can be used, varying the number of cells and thus the voltage later. This circuit also includes an object called an “antenna” which for these purposes can be any conductor, but an aluminum can works well.

bulb

bulb

P-channel

N-channel

Antenna

6 to 12 V

First determine whether you have the right voltage in your “power supply” which means enough but not too many cells in your battery pack. Connect a spare wire from the antenna to the negative terminal of your battery pack. One bulb should be lit, the other one not. Disconnect that wire and then run it from the antenna to the positive end of your battery pack. The bulb that was lit should be off and the other one should be lit. If neither bulb will light in either case, try again with more cells in series in your power supply. If both bulbs are lit in both cases, try again with fewer cells in your power supply. Disconnect the spare wire when done with this step.

Once you have the right number of cells in your battery pack, use the antenna to turn both cells off. This should be possible by connecting the spare wire between the antenna and *some point in the middle of your battery pack* (a point between some of the cells on the more positive end and some of the cells on the more negative end of the pack).

**And now the magic:** You may have already seen some of the magic happening, but once both bulbs are off, rub some objects together to make a positively charged object and a negatively charged object. (This can be done with any of the standard *triboelectric* methods of static electricity such as rubbing a PVC rod with wool or rubbing an acrylic rod with silk.)

Bring the positively charged object *near* (but not in contact with) the antenna. Record your observations. Be very specific about which bulb is lighting and when. Note that one bulb is connected to the P-channel transistor while the other is connected to the N-channel transistor.

Bring the negatively charged object near the antenna. Record your observations.

Based on your observations…

1. When is the resistance of a P-channel transistor *high*?
2. When is the resistance of a P-channel transistor *low*?
3. When is the resistance of an N-channel transistor *high*?
4. When is the resistance of an N-channel transistor *low*?

Feel free to play with the circuit a bit before moving on. Record your observations below.

**Part II: A controlled voltage signal**

In this part of the experiment you will measure the voltage and current “characteristics” of a MOSFET resistor in a way that electrical engineers would approve. Electrical engineers use the phrase “characteristic curve” to refer to a very specific plot of voltage and current.

Starting with the previous circuit, replace the light bulbs with 10 Ω resistors (the exact resistance is not important, so substitute with another resistance if needed). This removes the non-linear and unpredictable light bulbs and replaces them with consistent and linear circuit elements.

Insert a current probe (the box labeled “A” in the diagram below) and a voltage probe (the box labeled “V” on the right) to measure the current through and the voltage across one of the transistors. We will use these to measure “transistor current” and “transistor voltage” from which we can calculate the resistance of the transistor. Another voltage probe or voltmeter will be used to measure the voltage between the antenna and the negative end of the battery pack. This is the “gate voltage” or the voltage of the signal being sent to the gate by the antenna.

10 Ω resistor

10 Ω resistor

Antenna

gate

voltage

V

V

A

transistor

voltage

transistor current

Finally, connect a spare wire to the antenna. Connect the other end of the wire to the negative end of the battery pack. The gate voltage should be zero. Record the current through and the voltage across the transistor. Repeat this experiment by connecting the end of the spare wire in turn to every gap between batteries until you reach the positive end of the battery pack. You should have one more measurement than you have batteries in your pack. Record your results.

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| Transistor type: |  |  |
| Gate voltage | Transistor current | Transistor voltage | Transistor resistance |
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**Optional: A more precise measurement**

In the previous experiment, you may have found that the resistance of the transistor varied by a factor of thousands when the gate voltage changed by one volt. Another element must be added to get a description of the gradual variation of resistance with smaller changes in gate voltage.

10 Ω resistor

10 Ω resistor

Antenna

100 Ω resistor

variable

resistor

gate

voltage

V

V

A

transistor

voltage

transistor current

In parallel with the battery pack, insert a static resistor in series with a variable resistor. The static resistor is shown with a resistance of 100 Ω, but precise resistances are unimportant as long as the variable resistor has a range that varies between one percent of the resistance of the static resistor (or less) to at least one hundred times the resistance of the static resistor (or more). Connect the free end of the spare wire (connected to the antenna on one end) to the gap between the static resistor and the variable resistor. By changing the settings on the variable resistor you should be able to adjust the gate voltage in increments at least as small as a tenth of a volt.

Look at your data from the previous page to decide what range of gate voltages would be most useful to explore to better characterize the response of the MOSFET to gradual changes in gate voltage. Record your data.

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| Transistor type: |  |  |
| Gate voltage | Transistor current | Transistor voltage | Transistor resistance |
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Discuss your results with your lab partners, your classmates, and your instructor. Decide on a graphical way to present your data, and prepare a graph that shows the characteristics of this transistor. Due to large variations in behavior, you might consider the use of a logarithmic scale for your graph.

Ideas for types of graphs: You could prepare a “resistance graph” of transistor resistance as a function of gate voltage, but if you do then keep in mind that the range of resistances is very large. Alternatively you could present a graph of current as a function of voltage which is what electrical engineers refer to as a “characteristic curve.” A third alternative would be to present a graph of electrical power as a function of gate voltage, which would be referred to simply as a “power graph”. You and your lab partners may come up with other ideas.

**Optional: If using two MOSFETs, repeat part II for the other transistor.**

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| --- | --- | --- |
| Transistor type: |  |  |
| Gate voltage | Transistor current | Transistor voltage | Transistor resistance |
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**Part III: Conclusions**

You may have guessed that the “P” in PNP and P-channel stands for positive, while the “N” in NPN and N-channel stands for negative. N refers to semiconductors contaminated or “doped” with extra “negative charge carriers” (also known as electrons). Phosphorus and arsenic are common N-type dopants (adding negative charge carriers). The P refers to materials doped with extra carriers of positive charge, also known as holes. Boron and gallium are P-type dopants.

The structure of a PNP transistor is similar to the structure of a P-channel MOSFET. In both cases there is a region of N-doped material (connected to the gate or base) surrounded on either side by P-doped material (connected to the collector and emitter, or source and drain).

You have seen that transistors can vary their behavior with a wide range of resistances. Still, for simplicity, electrical engineers often refer to transistors as being in the “on state” (conducting with low resistance) or the “off state” (insulating with high resistance). P-channel and N-channel transistors are in the on state when the central channel (connected to the gate) is exposed to different electric potentials, one high and one low.

Based on your results…

A P-channel transistor is in the on state when the central channel (gate) is connected to high potential or low?

An N-channel transistor is in the on state when the central channel is connected to high potential or low?

Confusing? Try thinking about potential energy instead of potential, remembering that we are dealing with two different kinds of charge.

A ***P-channel*** transistor is in the ***on state*** when the central channel is connected to a potential that makes the ***potential energy*** of ***P charges*** high or low?

An ***N-channel*** transistor is in the ***on state*** when the central channel is connected to a potential that makes the ***potential energy*** of ***N charges*** high or low?

You can find many excellent diagrams and animations which illustrate how this happens. For every kind of transistor, the crucial transition happens when the potential energy of the needed charge carriers is reduced which allows electric current to flow through the transistor.