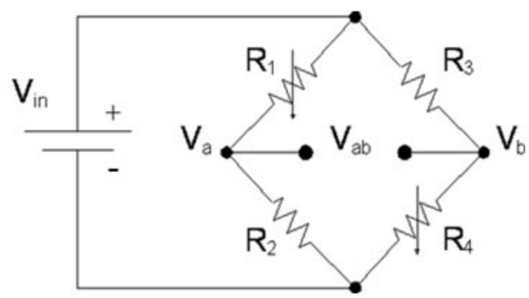
Modeling a Micro Pressure Sensor Activity

Participant Guide

Description and Estimated Time to Complete



In this activity you will use basic materials to build a macro-sized model of a micropressure sensor with a Wheatstone bridge sensing circuit *(circuit right)* on a flexible diaphragm. The results will simulate a micropressure sensor *(see Introduction)*. To test your sensor, you will apply variable pressures to the diaphragm while monitoring the resistance change and resulting voltage output of the bridge. In Part II of this activity you will use a set of weights to create a calibration curve for your particular pressure sensor model.

The unit Wheatstone Bridge Overview, explains the operation of a Wheatstone bridge. If you haven't already reviewed this unit, you should review it before you test your micropressure sensor model. Complete this activity through "Making a conductive bridge pattern". As your pattern dries, review the Wheatstone Bridge Overview. This will help you to better understand the workings of this device and the results of your testing.

Estimated Time to Complete
Allow at least two hours to complete this activity.

Micro Pressure Sensor Applications

Micropressure sensors are MEMS (microelectromechanical systems) designed to measure absolute or differential pressures. They convert physical quantities such as air flow and liquid levels into pressure values that are measured by an electronic system. Micropressure sensors can be used in conjunction with other microsensors such as temperature sensors and accelerometers for multisensing applications or other components.

In the automotive industry, micropressure sensors monitor the absolute air pressure within the intake manifold of the engine. Such MEMS are also being designed to sense tire pressure, fuel pressure, and air flow.

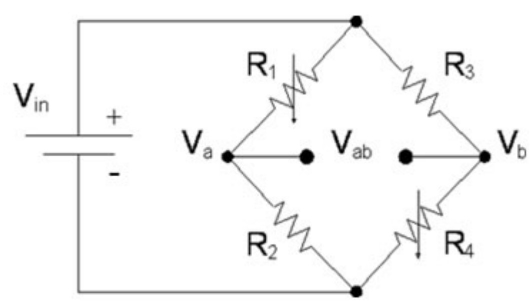
In the biomedical field, current and developing applications for micropressure sensors include blood pressure sensors *(see photo right)*, single and multipoint catheters, intracranial pressure sensors, cerebrospinal fluid pressure sensors, intraocular pressure (IOP) monitors, and other implanted coronary pressure measurements. The photo shows three blood pressure sensors on the head of a pin. These sensors were developed by Lucas NovaSensor to measure blood pressure and provide an electrical output representative of the pressure. RF elements are incorporated into the MEMS device allowing the sensor to transmit its measurements to an external receiver.

MEMS Blood Pressure Sensors on the head of a pin. [Photo courtesy of Lucas NovaSensor, Fremont, CA]

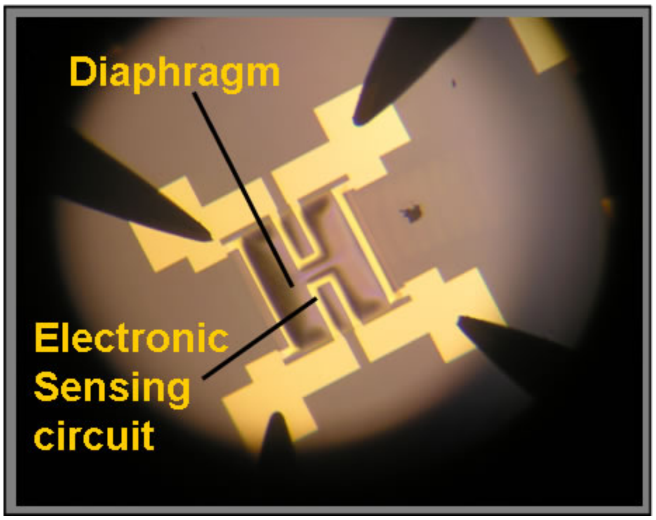
Micropressure sensors are also incorporated into endoscopes for measuring pressure in the stomach and other organs, infusion pumps for monitoring blockage, and noninvasive blood pressure monitors. Applications of micropressure sensors within the biomedical field and other industries are numerous.

A Micro Pressure Sensor

Many micropressure sensors use a Wheatstone bridge configuration as the sensing circuit. In MEMS sensors the Wheatstone bridge circuit is mounted on a membrane or diaphragm. The resistors in the Wheatstone bridge are made of a piezoresistive material, a material which experiences a change in resistance when mechanical stress is applied.



In the example below, a conductive material such as gold is used for the bridge circuit. The pressure sensor diaphragm is a thin layer of material (in this case, silicon nitride) which is resistant to chemical change *(see image below)*. The diaphragm seals the top of a cavity which is use as the reference pressure chamber. The other side of the cavity is open to the environment (in many cases) and subject to air pressure variation. As the diaphragm moves due to pressure differences between the top and the bottom of the diaphragm, the membrane expands and stretches. The bridge resistors mounted on the membrane also expand and stretch. This expansion of the bridge translates to a change of resistance in the conductive material of the bridge. As the conductive material stretches, its resistance increases. This increase in resistance causes a change in the measured output voltage of the Wheatstone bridge circuit. This voltage change is translated into a proportional pressure change on the diaphragm.



Micro Pressure Sensor illustrating the Wheatstone bridge and the Silicon Nitride Membrane (Diaphragm)
[Image of a pressure sensor built at the Manufacturing Technology Training Center (MTTC) at the University of New Mexico (UNM)]

All materials have electrical resistance. The resistance to electrical current flow of an object (resistor) is related to a material property called resistivity (ρ), and its geometry - length, width, and thickness. It is the combination of the geometry (shape) and material property (resistivity) which determines the overall electrical characteristic (resistance). To calculate the resistance (R) of a material, one can use the following formula:

$$R = \rho \frac{L}{A}$$

where L, and A are the length and cross-sectional area of the resistor, respectively. In the case of a rectangular cross section, the area can be written as

$$A = t \times w$$

where t and w are the thickness and width of the structure, respectively.

In the Wheatstone bridge application presented in this activity, the resistivity, ρ, is a physical property of the material. Resistivity remains constant under constant temperature and stress (e.g., pressure). It should be pointed out that the resistivity of a material, ρ, is inversely proportional to its conductivity, σ:

$$\sigma = \frac{1}{\rho}$$

As the conductive (resistive) material stretches, the length increases while the area decreases. This increase in length and decrease in area results in an increase in overall resistance.

You may ask, " I understand why the resistor gets longer when the membrane it is adhered to stretches, but why does the cross sectional area decrease?" If you consider that the overall mass of the resistor (the total amount of the material) does not change due to the conservation of mass principal, and that the density of the material doesn't change either, you can therefore assume that the total volume of the resistor has to stay constant. Since volume, V, can be written as a product of length (L) and area (A),

$$V = L \times A$$

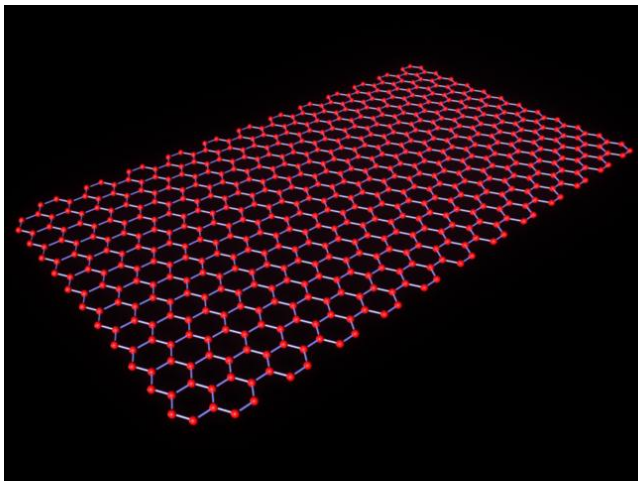
then as *L* gets longer, *A* must get smaller in order for the volume to remain constant.

NOTE: We have assumed the density of the material does not change; however, it could, if the temperature of the material changes. Therefore it is critical for the bridge circuit design to automatically compensate for temperature fluctuations (which could occur in a wide variety of applications).

To re-cap, one can now see from the resistance equation, $R = \rho \frac{L}{A}$, that as a conductor stretches, the length increases as the cross-sectional area simultaneously decreases resulting in the L/A ratio in the equation to increase.

What is Graphene?

In this activity you will be using graphite to construct the electronic circuit. Graphite consists of stacks of graphene sheets. So what is graphene? Graphene is a material formed when carbon atoms arrange in sheets. Graphene is a one-atom-thick planar sheet of carbon atoms densely packed in a honeycomb crystal lattice *(as shown in the graphic below)*. Graphene is also used as the structural element for fullerenes such as carbon nanotubes and buckyballs. In this activity, the mixture of graphite (pencil lead) and rubber cement used to construct the Wheatstone bridge contains sheets of graphene. These sheets are thought to slide on top of each other as the material stretches while still maintaining contact. You should see the effect of this when you apply pressure to your pressure sensor model diaphragm.



Graphene Sheet
Graphite is composed of several stacked sheets of graphene

Activity Objectives and Outcomes

Activity Objectives

- Explain how a change in length and cross-sectional area affects a material's resistance.
- Using your micropressure sensor model, demonstrate and explain how pressure affects the resistance and output voltage of a Wheatstone bridge sensing circuit.

Activity Outcomes

In this activity you construct a macro-sized model of a micropressure sensor with a Wheatstone bridge sensing circuit on a flexible diaphragm. Once constructed, you test the operation of the sensor and then create a calibration curve that represents your models response to pressure changes.

Upon completion of this activity, you should be able to answer the following questions:

- How does the length of a conductive material affect its resistance?
- What is meant when a Wheatstone bridge is balanced?
- What are some applications of pressure sensors in microsystems technology?
- What are the advantages and disadvantages of using a Wheatstone bridge sensing circuit in the micro and nano-scales?

Resources

SCME Micro Pressure Sensors & The Wheatstone Bridge Learning Module

Teamwork

Working with one to two other participants will promote a better understanding of this activity.

Facilities / Workspace / Safety Precautions

You will need a flat table as a workspace.

For safety, it is recommended that you wear safety glasses and latex or nitrile gloves when working with the graphite and rubber cement.

Supplies / Equipment

Supplies provided by Instructor

- Safety glasses and gloves
- Wipes or paper towels
- Metric Ruler
- 1 bottle of Rubber cement
- Scissors
- Blue painter's tape 1" (or electrical tape)
- 6 large paperclips
- Small brush (to brush out mortar)
- Multimeter with clip-on leads
- Marker (e.g., "Sharpie")
- 1 small sheet of cardstock (thick paper)
- Ice pick or large nail

Supplies included in SCME Kit*

- 2 quart paint cans (empty and unused)
- 6 Balloons (12 ") (shown)
- Pencil Lead (0.9 mm thick HB hardness) – 2 packs 15 leads each (shown)
- Mortar and pestle (shown)
- Copper foil tape ¼" wide – conductive on both sides (3M) (shown)
- Four 3 cc (3 mL) Plastic Syringes with tip (shown)
- Two (2) leads with alligator clip at each end (Leads should be the same length)
- Two plastic cups or glass vials
- 3 volt source, AAA battery holder with leads and alligator clips
- 2 AAA batteries or 2 AA batteries
- One Micro Pressure Sensors & The Wheatstone Bridge Learning Module - Instructor Guide
- One Micro Pressure Sensors & The Wheatstone Bridge Learning Module - Participant Guide

*If you do not have an SCME Kit, you can purchase these supplies and/or substitute with other items.

Documentation

Write a report to include the following:

- Hypothesis and predictions
- Your procedure
- Any problems that occurred and how these problems affected the outcome
- All of your measurements
- An analysis of the results (Did the outcome agree with your hypothesis and predictions?)
- Answers to the Post-Activity questions.

Expectations

This activity allows you to build and explore the operation of a Wheatstone bridge strain-based transducer. Hypothesis: Write a statement that describes what you expect as an outcome.

Make predictions:

- What factors will affect the outcome?
- What effect will a change in applied pressure have on the circuit's resistance? Why?
- What effect will a change in applied pressure have on the circuit's voltage? Why?

Preparation / Setup

Gather all of the supplies for this activity. Set up a workspace on a flat table top large enough for all of the materials and for at least two students to work together to build this device.

Activity: Modeling a Micro Pressure Sensor

Description: Using an empty paint can, balloon and ground mechanical pencil lead (graphene) mixed with rubber cement, build a macro-sized model of a micropressure sensor using a Wheatstone bridge sensing circuit.

Safety

a. From the Internet, download a Material Safety Data Sheet (MSDS) for rubber cement.
b. Answer the following questions relative to rubber cement.
    a. What are two hazards of rubber cement that you need to be constantly aware of?

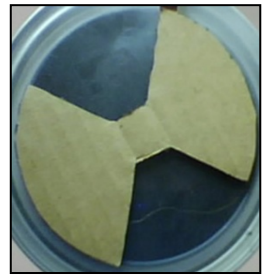
    b. What type of personal protective equipment should you wear when handling rubber cement?

    c. What conditions should be avoided when working with rubber cement?

Building the Pressure Sensor Model

Constructing the Diaphragm

Figure 1.



Remove the lid from the paint can (if applicable).

1. Using the ice pick or nail, punch a hole in the side of the paint can. The hole should be big enough to insert the TT tip of a syringe.
2. Using the stencil provided (see attached at the end of this document), cut the bridge pattern from a piece of the cardboard or cardstock. (Figure 1)
3. Cut the neck off the balloon to about 4 cm from top opening or at least 1 cm below the curvature of neck (Figure 2)
4. Stretch the balloon tightly over the open end of the paint can. (Figure 3). You want an “even” stretch.
5. Secure the edges of the balloon to the can with painter’s tape. (Figure 4)

Figure 2

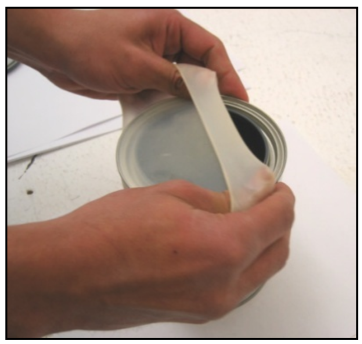


Figure 3

Figure 4

Creating the leads and bridge pattern

1. Center the template over the balloon diaphragm as shown in Figure 1.
2. Outline the pattern with a marker onto the top of the diaphragm. Remove template from diaphragm. *(Figure 5)*
3. Cut four – 6-8 cm strips of conductive copper tape.
4. Remove the backing off one strip of conductive tape. Place one end of the tape on the membrane (balloon) at one of the four "nodes" and on top of part of the "circuit" as shown in Figure 6. Limit the contact of the copper tape with the "circuit" to about 1 cm.
5. Pinch the middle of the strip of tape to create a tab and attach the other end of the conductive tape to the side of can (as shown in Figure 6). The tab will be used to connect the meter leads for measuring resistance and voltage.
6. Repeat steps 5 and 6 with the other three leads (strips of conductive tape). *(See Figure 6 for placement of all four pieces of conductive tape)* To hold the ends of the copper tape in place, you could add another strip of blue tape around the side of the can, over the tape ends as shown in Figure 7.

Note: The resistance of the copper tape is very low relative to the graphite/rubber cement mixture; therefore, at the nodes, where the graphite mixture is applied on top of the copper tape, current will flow through the tape (path of least resistance) and not the graphite mixture. Minimizing the amount of copper tape IN the circuit, will yield the best results.)

Figure 5
(Template outline)

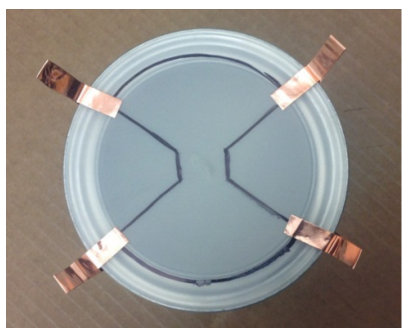


Figure 6
(Copper Tape Placement)

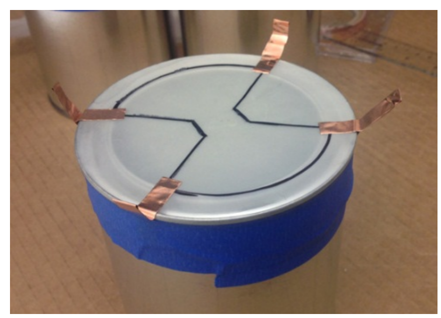


Figure 7
(Securing the copper tape)

<u>Making the conductive material (carbon paste)</u>

1. **Put on gloves and safety glasses.**
2. Carefully break one pack of the graphite leads (15 pieces) into small pieces and place in the mortar.
3. Grind the graphite into as fine of a carbon powder as possible. Grind until you see no “grain pieces” and the graphite is a powder. The finer the better. You will be mixing this powder with rubber cement and then forcing the mixture through a syringe tip. A small graphite chunk could clog the syringe.
4. Pour the carbon powder into the small plastic cup or glass vial. Use a small brush to get all of the carbon out of the mortar.
5. Using the syringe with tip attached, extract 3 ml of rubber cement from the rubber cement bottle.
6. Transfer the rubber cement to the cup or vial containing the graphite powder.
7. Unfold a large paperclip. (This will be your stirring mechanism.)
8. Using the paperclip, stir the powder and rubber cement mixture to incorporate the graphene throughout the liquid. The color of the mixture should be black, and the viscosity (thickness) should be close to that of rubber cement. If it is too thick, add a little more rubber cement. If too thin, add more carbon powder. (A comment – You will be applying this graphite/rubber cement mixture onto the diaphragm in the same manner as decorating a cake; therefore, the viscosity of the mixture should similar to that of toothpaste.

Your conductive material is now made and ready for use.

Making a conductive bridge

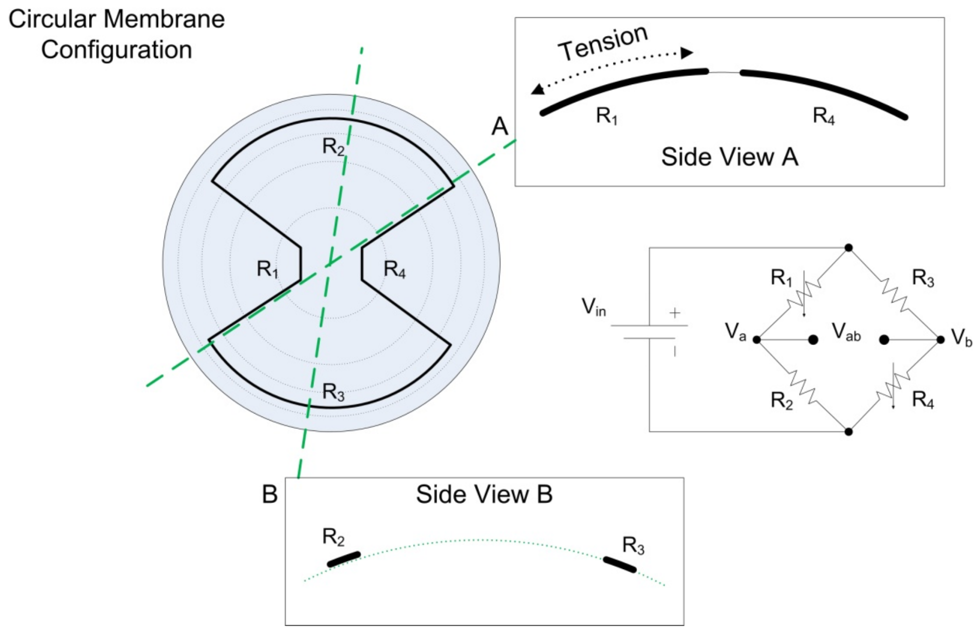
1. Using the syringe, pull the graphene mixture from the cup or vial into the syringe. Fill the syringe with the mixture.
2. To eliminate the air from the syringe, insert the paperclip into the tip of the needle, through the liquid and into the air gap at the top of the syringe.
3. Burp the air from the syringe, by gently compressing the liquid in the syringe until a little comes out of the needle. **Note: It is important when filling the syringe that there are no air bubbles because when applying the conductive material it is essential that there are no gaps in the lines.*
4. If the syringe does not have at least 2 ml of liquid, place the syringe tip back into the cup and continue to fill the syringe to the 2 ml mark.
5. Using a wipe or paper towel, wipe the tip clean.
6. Using the syringe, carefully apply about a 1 to 2 mm line (width) of your conductive material (rubber cement and graphene mixture) following the pattern transferred from the template. Try to keep the width and height of the carbon/cement line consistent. Be sure to flow ON TOP of and over the copper wire at the bridge corners (nodes). You need to make good electrical contact. *(Figure 8)*
7. Check for any "opens" in your circuit. Close them with the graphene solution.

Figure 8
(Conductive material placed on pattern and on top of conductive tape)

You have now created a micropressure sensor model with a Wheatstone bridge.

8. Before testing your bridge circuit, you should let it set **for at least** 30 minutes.
9. Any remaining mixture can be shared or tossed.
10. Clean or properly dispose of the syringe.

Testing your Pressure Sensor (Measuring Resistance)



The above diagrams are of the pressure sensor Wheatstone bridge in a circular configuration. This is the circuit you constructed in the previous steps of this activity. When comparing the actual circuit components to the Wheatstone bridge circuit, resistors R_2 and R_3 are configured parallel to the edge of the can, and hence, will not stretch as much when the membrane expands. Resistors R_1 and R_4 are configured over the open part of the membrane or can, parallel to the radius, and will be subject to the highest tension (stretching), experiencing the greatest piezoresistive effect.

To help you better relate to the specific resistors in your circuit, label your circuit with specific resistor notation (R1, R2, R3, R4).

So let’s see how your circuit works.

1. Clip one of the leads from the multimeter to one of the nodes (copper tabs).
2. Clip the other multimeter lead to the "opposite" node as shown below in *Figure 9*. Do not hook the battery up yet, you will only be measuring resistance of the circuit.

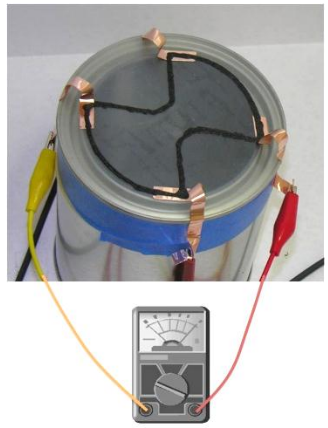


Figure 9

3. Gently press down a couple of times on the diaphragm to pre-stretch it.
4. Set your multimeter to read resistance.
5. Record your reference circuit's total resistance. R_R = __________________
   (*NOTE: The multimeter may indicate a continual drop in pressure as the diaphragm comes to rest at its reference position.)*
6. Gently push down on middle of the balloon. You should see the resistance change.

Recording resistance

7. Ask the instructor for three (3), 50 gram weights. These weights will simulate an "applied pressure". Since they are conductive, you will need to place a small piece of paper in the center of the diaphragm on top of this circuit. This paper acts as an insulator to keep the weights from shorting out your Wheatstone bridge circuit.
8. Place one of the weights on top of the piece of paper. Record the resistance below.
9. Add the second weight and record R_2, then the third weight, and record R_3.

   a. R_1 = ___________________
   b. R_2 = ___________________
   c. R_3 = ___________________

10. Remove the weights from the diaphragm. *(NOTE: Because of the elasticity characteristics of the balloon, your resistance reading may not return to the original reference resistance once the applied pressure (weights) is removed. The balloon may lose some of its original elasticity as increased pressures are applied.)*

11. How did the applied pressure affect the resistance of the bridge?

____

12. Explain how the following formula relates to your Wheatstone bridge circuit.

$$R = \rho \frac{L}{A}$$

13. Draw the equivalent circuit with the resistance meter hookup in the space below.

Now let's apply some voltage to your circuit.

Testing your Pressure Sensor (Measuring Voltage)

14. Using the other two leads with alligator clips, attached a voltage source (2 AAA batteries) across the bridge circuit. Follow the setup shown in the photograph below *(Figure 10.) (NOTE: When hooking up a voltage source, always connect the ground lead (- lead) first.)*

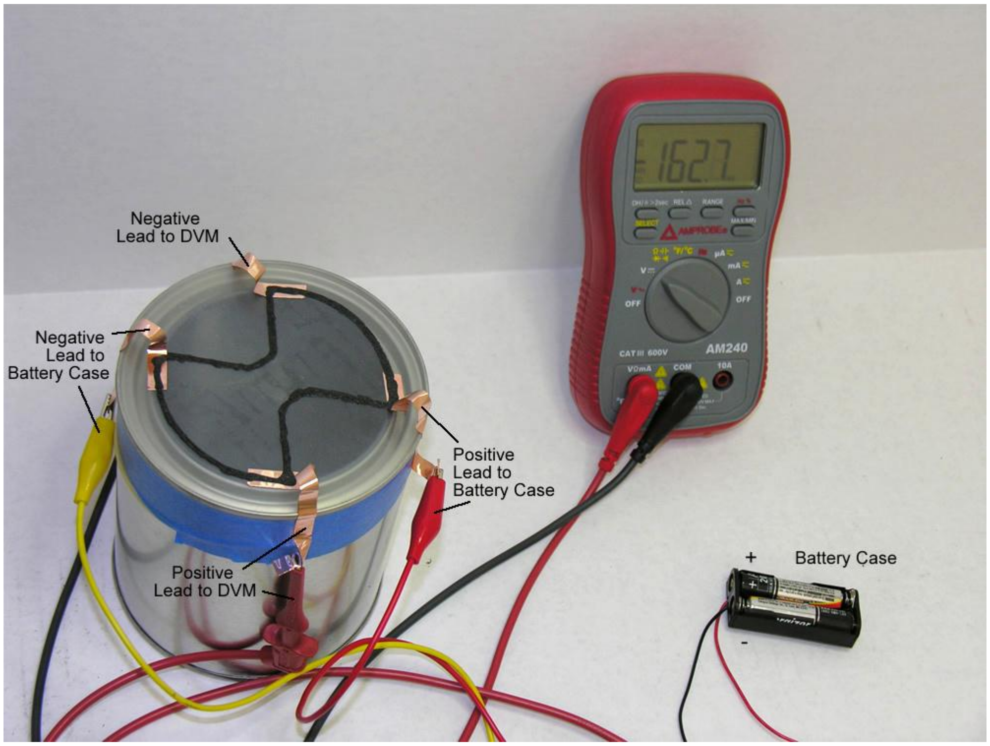


Figure 10 (Hookup for Voltage Measurements)

15. Switch meter to measure voltage. (You might need to adjust the range to read mVolts.)
16. Record initial voltage. V_R = ________________________

NOTE: A balanced bridge should have a zero voltage as V_R. Why does your bridge not measure zero?

17. Place one of the weights in the middle of the diaphragm (on top of the paper).
18. Record the voltage for three pressures (1, 2, and 3 weights).
    a. V_1 = ___________________
    b. V_2 = ___________________
    c. V_3 = ___________________
19. How did the applied pressure affect the voltage across the bridge?

    ____

The following steps allow you to further explore this device and the effects that pressure has on the resistance and voltage of a Wheatstone bridge sensing circuit.

20. Pull an empty syringe to about 1.5 ml of air. Place the tip of the syringe into the hole in the side of the can. Make it snug and as airtight as possible.
21. You can now simulate increases in pressure (pushing on the syringe) and decreases in pressure (pulling on the syringe).
22. Test your pressure sensor model using various changes in pressure.
23. This model could also be used to show how a micro pressure sensor is affected by temperature. Experiment with ways to increase or decrease the ambient temperature or the temperature of the air trapped inside the can. Study the effects on the circuit's output.

Post-Activity Questions

1. In the above procedure, what factors could have an effect on the outcome (the resistivity of the bridge circuit)?

2. What is meant by the "reference" voltage or reference resistance of the Wheatstone bridge? Does this stay consistent? Why or why not?

3. What determines the reference voltage / resistance?

4. What causes a change in resistance or voltage?

5. Describe three (3) MEMS that use a diaphragm pressure sensor.

6. How could this pressure sensor model be improved upon?

Modeling a Micro Pressure Sensor Activity – Part II: Creating Calibration Curves

Modeling a Micro Pressure Sensor Worksheet
Creating Calibration Curves

Team Member Names: ___________________   ___________________   ___________________

Turn in one worksheet for each team – make sure it is very neat and legible.

Make the Pressure Sensor Model as described in the SCME Modeling a Micro Pressure Sensor Activity.

1. Set up the volt-meter as directed by the instructor.
    i. Measure the resistance across the bridge: ________________ Ω

2. Add the battery as directed.
    i. Measure the voltage across the bridge: _________________V

3. Push *slightly* on the membrane and see the change in the voltage output.
    i. What was the voltage (approximate) you observed: ______________V

4. Release your finger – observe that it takes time for the voltage to return and that it does not always return to the original, nominal value. Why do you think that is?

____

____

____

How do you determine the relationship of Voltage to actual pressure? The process to determine this is called "calibration." Every sensor is slightly different from every other sensor.

One way to calibrate your sensor is to place 50 gram washers, one at a time, on top of the membrane and measure the resulting voltage outputs. The washers ***simulate air pressure being applied and distributed across the entire membrane***; therefore, to calculate the pressure "on the membrane" we use the weight of the washers as the force applied, divided by the surface area of the membrane.

(Following on units, unit conversions and formulas)

Pressure Units = Force/Area = N/m^2 (Newtons per meter squared)
1 N/m^2 = 1 P (Pascal)
= 10^{-5} bar
= 9.87×10^{-6} atm (atmosphere)
= 7.50×10^{-3} Torr
= 1.45×10^{-4} psi (pounds per square inch)

1 Newton = 1 kg * (meter/sec^2) or $1\ kg * \frac{m}{s^2}$

Area of the membrane = _______________ m^2 ($A = \pi r^2$)

g = acceleration due to gravity = $9.8 m/s^2$
m=mass in kg (grams/1000)

Data Table

Trial #	**Mass (g)**	**Mass (kg)**	**Force (m*g) kg *m/s^2 = N (Newtons)**	**Pressure = F/A N/m^2 = P**	**Voltage (V)**
Trial 1					
1	50	0.05	0.490		
2					
3					
4					
5					
6					
7					
8					
Trial 2					
1					
2					
3					
4					
5					
6					
7					
Trial 3					
1					
2					
3					
4					
5					
6					
7					

Calibration Curve

Plot the Data –Voltage (output) Vs Pressure (input) – three curves on one graph, one curve for each trial. Label your axes, curves, and title your chart. (You can use the graph below or enter your data into a spreadsheet program (e.g., Excel) and plot your curves.

Post Activity Questions

1. What is the relationship between force and applied pressure (e.g., linear, exponential, parabolic)?

2. Did you get the same curve for each trial?

   If not – give some reasons why this may be.

3. Heat or cool the can. How does a change in temperature affect the pressure in the reference chamber?

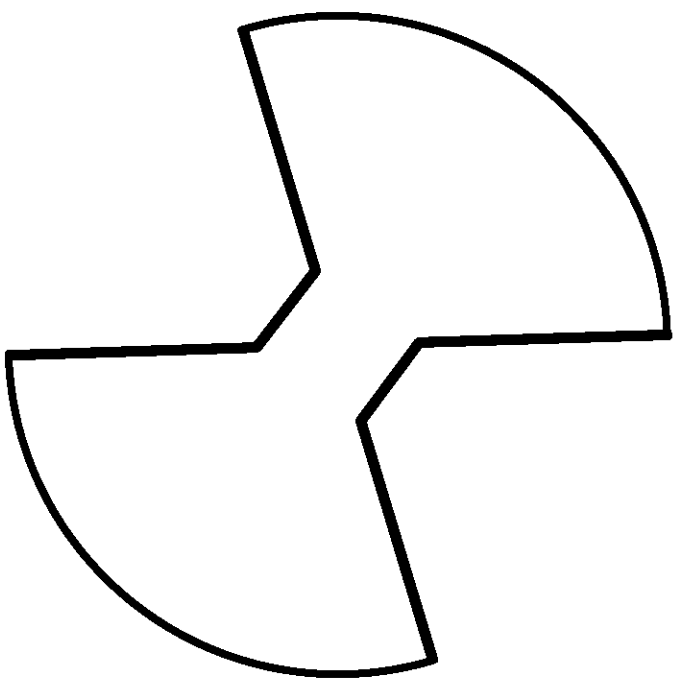
4. Repeat a trial with the new temperature. How does a change in temperature affect the calibration curve?

Summary

A common micropressure sensor uses a Wheatstone bridge sensing circuit on a flexible diaphragm. A change in pressure creates a deflection of the diaphragm. This deflection causes the variable resistors of the bridge to expand, increasing circuit resistance indicating a change in pressure. The amount of change in resistance is proportional to the change in pressure from reference pressure to applied pressure.

Related SCME Units

- Wheatstone Bridge Overview unit
- Wheatstone Bridge Derivation Activity
- MTTC Pressure Sensor Process Learning Module



If using a one-quart paint can, this template should print out to approximately 3 3/8" (8.57 cm) in diameter and can be used as a template to trace out the piezoresistive Wheatstone bridge structure.

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