Southwest Center for Microsystems Education (SCME)
University of New Mexico

MEMS Introduction Topic

Pressure Sensor Model Activity

Shareable Content Object (SCO)

This SCO is part of the Learning Module
Wheatstone Bridge Overview

Target audiences: High School, Community College.

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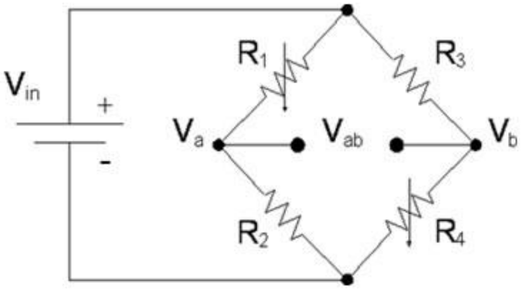
Pressure Sensor Model Activity

Wheatstone Bridge Overview Learning Module Participant Guide

Description and Estimated Time to Complete

In this activity you will use basic materials to build a macro pressure sensor with a Wheatstone bridge sensing circuit *(circuit right)* on a flexible diaphragm. The results will simulate a MEMS pressure 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.



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 pressure 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.

MEMS Pressure Sensor Applications

MEMS pressure sensors are 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. MEMS pressure sensors can be used in conjunction with other sensors such as temperature sensors and accelerometers for multisensing applications or other components.

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

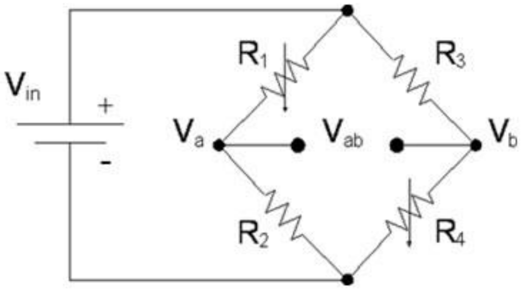
In the biomedical field, current and developing applications for MEMS pressure sensors include blood pressure sensors *(see photo right)*, single and multipoint catheters, intracranial pressure sensors, cerebrospinal fluid pressure sensors, intraocular pressure (IOP) monitors, and other implanted coronary 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]

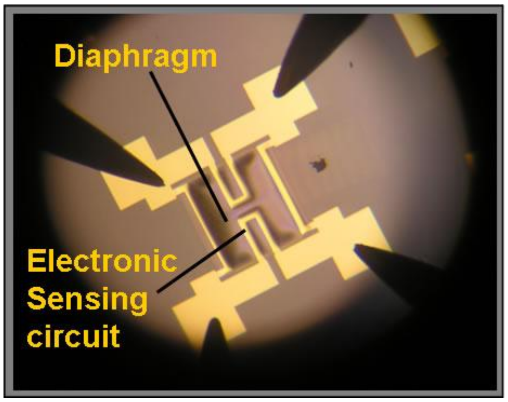
MEMS pressure sensors are also incorporated into endoscopes for measuring pressure in the stomach and other organs, infusion pumps for monitoring blockage, and noninvasive blood pressure monitors. Applications of MEMS pressure sensors within the biomedical field and other industries are numerous.

A MEMS Pressure Sensor

Many MEMS pressure sensors use a Wheatstone bridge configuration as the sensing circuit. In MEMS 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 changes its 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 which is resistant to chemical change such as, in this case, silicon nitride *(see image below)*. One side of the diaphragm is sealed to provide a reference pressure. The other side is open to the environment and subject to air pressure variation. As the diaphragm moves due to pressure changes, 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.



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),

$$V = L \times A$$

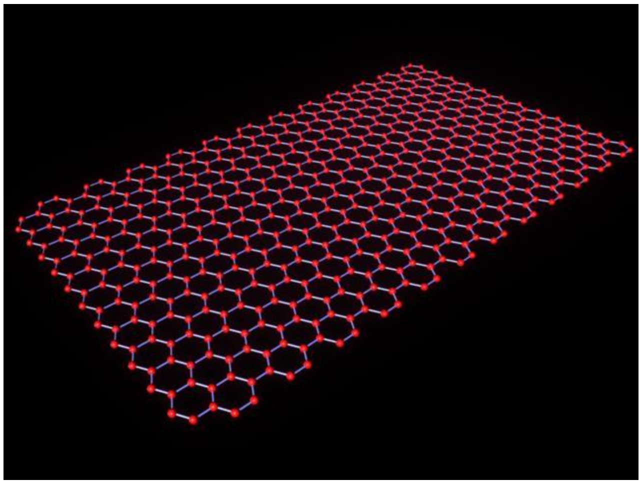
then as L gets longer, A must get smaller in order for the volume to remain constant.

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 pressure 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-size pressure sensor with a Wheatstone bridge sensing circuit on a flexible diaphragm. You also discuss microsystems applications. 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 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 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
- Double-sided tape
- Small brush (to brush out mortar)
- Multimeter with clip-on leads
- Marker (e.g., "Sharpie")
- 1 small sheet of cardstock (thick paper)
- One sheet of paper or cone shaped coffee filter
- 1 glass cup or bowl with a 8 to 10 cm diameter
- 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 Syringe with tip (shown)
- Two (2) leads with alligator clip at each end (Leads should be the same length)
- Two glass vials with cap size 20-25ml
- 3 volt source, AAA battery holder with leads and alligator clips
- 2 AAA batteries or 2 AA batteries
- One Wheatstone Bridge Overview Learning Module - Instructor Guide
- One Wheatstone Bridge Overview Learning Module - Participant Guide

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: Pressure Sensor Model

Description: Using an empty paint can, balloon and ground mechanical pencil lead (graphene) mixed with rubber cement, you will build a macro-size pressure 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.
    d. What conditions should be avoided when working with rubber cement?

Making the conductive material (carbon paste)

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 onto sheet of paper or into the coffee filter. Use a small brush to get all of the carbon out of the mortar.
5. Fold the paper/filter and carefully pour all of the powder into a glass vial.

6. Using the syringe with tip attached, extract approximately 3 ml of rubber cement.
7. Transfer the rubber cement to the vial containing the graphite powder.
8. Unfold a large paperclip, but leave the smaller looped end intact. (This will be your stirring mechanism.)
9. Using the paperclip, stir the powder and rubber cement mixture in the vial. The color of the mixture should be black, and the viscosity (thickness) should be close to the original 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.
10. Cap the vial and set aside.

Your conductive material is now made and ready for use.

Building the Pressure Sensor Model

Constructing the Diaphragm

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

1. Using the stencil provided (see template at the end of this document), cut the bridge pattern from a piece of the cardboard or cardstock. (Figure 1)
2. 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)
3. Stretch the balloon tightly over the open end of the paint can. (Figure 3). You want an "even" stretch.
4. Secure the edges of the balloon to the can with painter's tape. (Figure 4)

Figure 1.

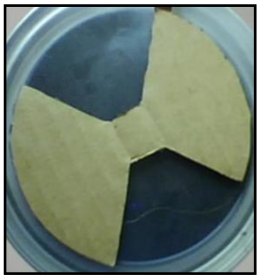


Figure 2

Figure 3

Figure 4

Creating the leads and bridge pattern

1. Place a strip of double-sided tape along the length of one side of the cardboard/ cardstock template. This will make it easier to trace.
2. Center the template (tape side down) over the balloon diaphragm and gentle press the template onto diaphragm.
3. Outline the pattern with a marker onto the top of the diaphragm. Gently remove template from diaphragm. *(Figure 5)*
4. Cut four – 8 – 10 cm strips of conductive copper tape.
5. Remove the backing off a strip of conductive tape. Place one end of the tape at one of the corners of the outline.
6. Attach the other end of the conductive tape to the side of can and create a "loop" above the diaphragm. Then place the end of the foil tape to the side of the can, leaving a 1 cm long "connecting" lead for an alligator clip. *(Figure 6) (Alternate method: Pinch the loop together to make a tab that can be used as the connector lead for an alligator clip as shown in Figure 7b.)*
7. Repeat steps 5 and 6 with the other three leads (strips of conductive tape). *(See Figure 7 for placement of all four pieces of conductive tape)*

Figure 5
(Template outline)

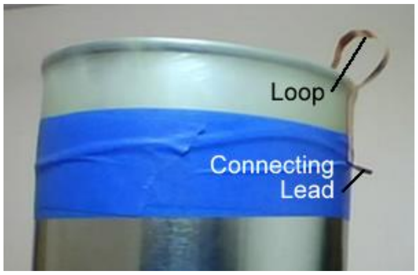


Figure 6
(Creating the connection)

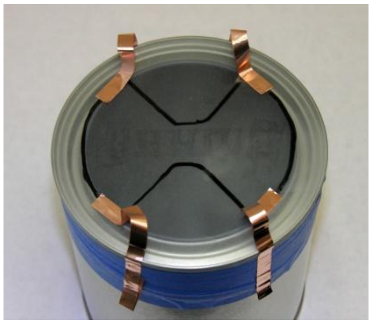


Figure 7
(Conductive tape placement)

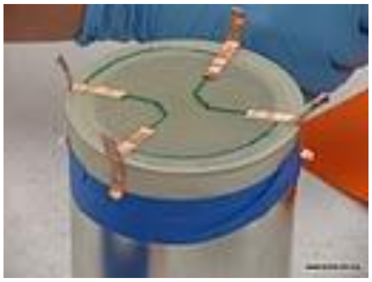


Figure 7b
(Alternate Conductive tape placement)

Making a conductive bridge pattern

1. Pull liquid from the vial with 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 vial 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 graphite 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. You need to make good electrical contact. *(Figure 8)*
7. Check for any "opens" in your circuit. Close them.

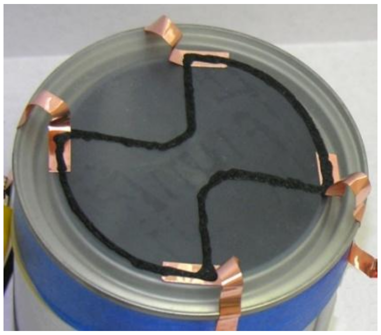


Figure 8
(Conductive material placed on pattern and on top of conductive tape)

You have now created a pressure sensor with a Wheatstone bridge.

8. Before testing your bridge circuit, you should let it set for 15 to 30 minutes.
9. Squeeze any unused graphite/cement mixture from the syringe, back into the vial.
10. Cap the vial. The remaining mixture should stay fluid for several weeks.
11. Clean or properly dispose of the syringe.

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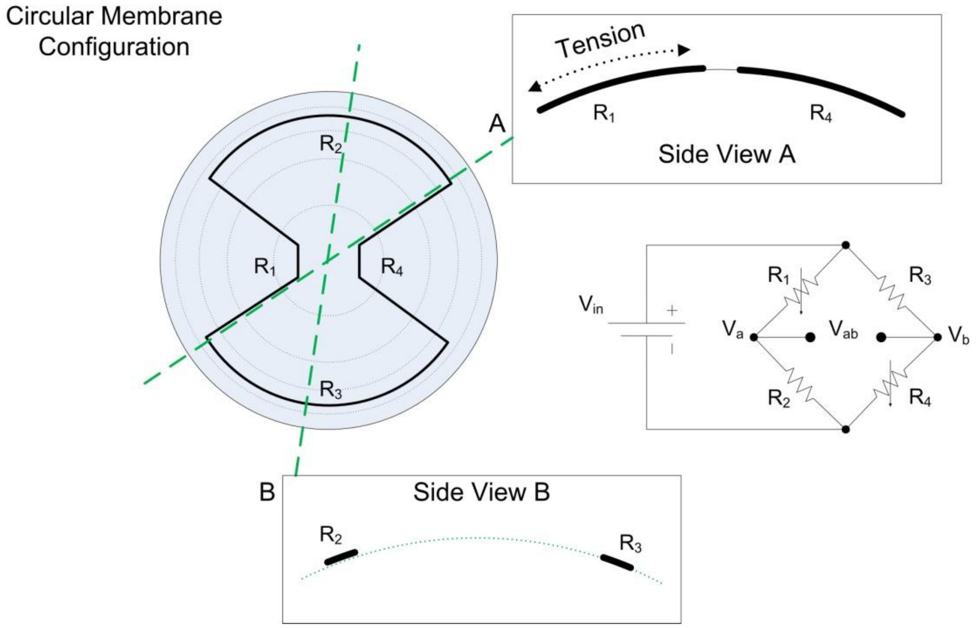
Testing your Pressure Sensor (Measuring Resistance)



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.

So let's see how this works.

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

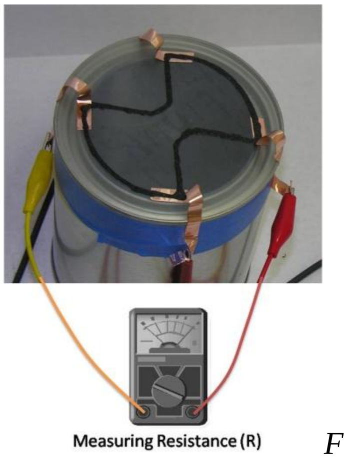


Figure 9

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.

NOTE: Be creative. Develop a systematic approach to "applying pressure". For example, you could use coins, small weights, marbles, or any of the same object that is heavy enough to "flex" the diaphragm. Of course if the object is conductive (e.g., coins), a balloon should be used as an insulator between the weights and the circuit.

7. Record the resistance for three different applied pressures, increasing the pressure before each recording.

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

   (NOTE: Because of the elasticity characteristics of the balloon, your resistance reading may not return to the original reference resistance once the applied pressure is removed. The balloon may lose some of its original rigidity as different pressures are applied.)

8. How did the applied pressure affect the resistance of the bridge?
   ____

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

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

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

Now let's apply some voltage to your circuit.

<u>Testing your Pressure Sensor (Measuring Voltage)</u>

11. Using the other two leads with alligator clips, attached a voltage source (2AAA 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.)*

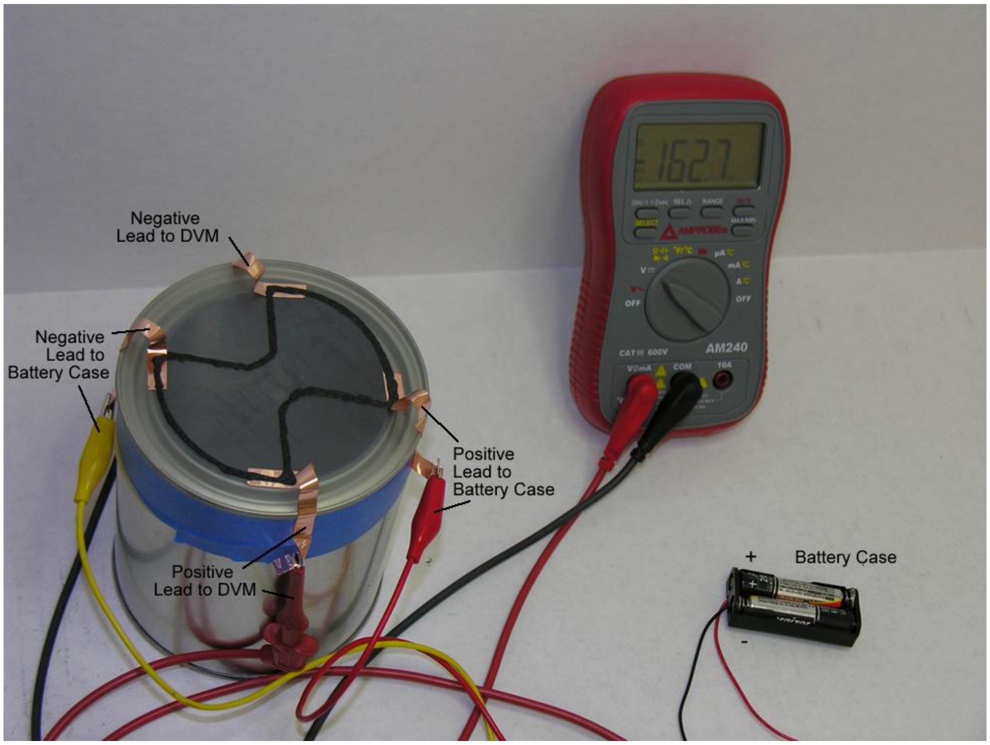


Figure 10 (Hookup for Voltage Measurements)

12. Switch meter to measure voltage.
13. Record initial voltage. V_R = ________________________

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

14. Press down on the middle of the diaphragm.
15. Record the voltage for three different pressures, increasing the pressure before each recording.
    a. V_1 = ___________________
    b. V_2 = ___________________
    c. V_3 = ___________________
16. How did the applied pressure affect the voltage across the bridge?
    ____

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

17. 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.
18. Pull an empty syringe to about 1.5 ml of air.
19. Place the tip of the syringe in the hole. Make it snug and as airtight as possible.
20. You can now simulate increases in pressure (pushing on the syringe) and decreases in pressure (pulling on the syringe).
21. Test your pressure sensor model using various changes in pressure.
22. This model could also be used to show how a MEMS pressure sensor is affected by temperature. Find 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

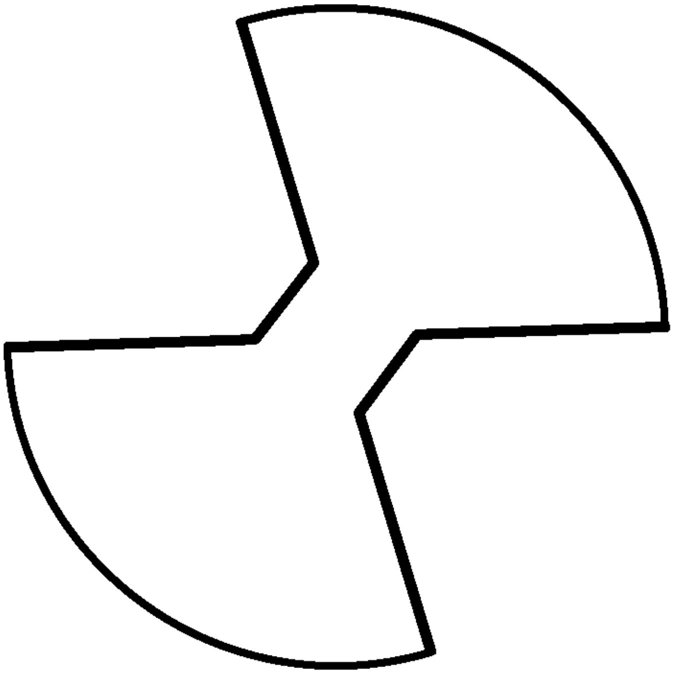
1. In the above procedure, what factors could have an effect on the outcome (the resistivity of the bridge circuit)?
2. What is meant by the “reference” voltage or reference resistance of the Wheatstone bridge? Does this stay consistent? Why or why not?
3. What determines the reference voltage / resistance?
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?

Summary

A common MEMS pressure 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 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.

Disclaimer

Activity Evaluation

The Southwest Center for Microsystems Education (SCME) would like your feedback on this activity. Your feedback allows SCME to maintain the quality and relevance of this material.

To provide feedback, please visit www.scme-nm.org . Click on SCO Feedback.

Your feedback is greatly appreciated.

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