
Introduction to Transducers

Primary Knowledge Participant Guide

Description and Estimated Time to Complete

This learning module is one of three SCME modules that discuss the types of components found in microelectromechanical systems (MEMS). This module covers “transducers” – what they are, how they work and how they are used in both macro and micro-sized systems. An activity provides further exploration into specific transducers and how they are used in everyday devices. Two related learning modules cover MEMS sensors and actuators.

In this lesson you will learn about transducers, what they are, what they can do, and various applications. You will be asked to identify transducers in both the macro and micro scales. The understanding of this information is important to microelectromechanical (MEMS) or microsystems technology.

Estimated Time to Complete

Allow approximately 45 minutes to an hour to complete this lesson. This lesson consists of this reading material and a short PowerPoint presentation that supports this lesson. You may view the presentation before or after reading through this lesson.

Introduction



Three types of transducers: light bulb, microphone, and electric motors

A transducer is any device that converts one form of energy into another. Examples of common transducers include the following:

- A microphone converts sound into electrical impulses and a loudspeaker converts electrical impulses into sound (i.e., sound energy to electrical energy and vice versa).
- A solar cell converts light into electricity and a thermocouple converts thermal energy into electrical energy.
- An incandescent light bulb produces light by passing a current through a filament. Thus, a light bulb is a transducer for converting electrical energy into optical energy.
- An electric motor is a transducer for conversion of electricity into mechanical energy or motion.

An actuator is a device that actuates or moves something. An actuator uses energy to provide motion. Therefore, an actuator is a specific type of a transducer. Which of the previously mentioned examples can function as an actuator?

Question:

Besides for the transducers mentioned here, what is another transducer found in your home?

Transducers and sensors usually work hand-in-hand. Many sensors consist of a transducer and the electronics needed to evaluate the transducer's input and output. Therefore, a sensor can be defined as a device that receives and responds to a signal. This signal is produced by some type of energy, such as heat, light, motion, or chemical reaction that, in many cases, is the output from a transducer. Once a sensor detects one or more of these signals (an input), it converts it into a readable representation of the input signal. The output of the sensor could be a readable scale, an analog readout or a digital readout. Based on this explanation of a sensor, you should see that sensors are used in all aspects of life to detect and/or measure many different conditions.

Let's take the example of a thermometer.

To the right are the images of both a mercury thermometer and a digital thermometer. The mercury thermometer contains a small reservoir of mercury in the tip. As the temperature of the mercury increase, the mercury expands and "moves up" the tube to a marking that represents the temperature. The digital thermometer uses a thermocouple (which converts heat to voltage). The varying voltage is used to indicate an increase or decrease in temperature.

We'll talk more about thermocouple

later. In both cases, energy is being converted by a transducer and then converted to a readable output.



Question: *What are some sensors that you are familiar with or use daily?*

This lesson describes the basic concepts of transducers and introduces transducers in both the macro and micro scales. The next lessons cover sensors and actuators.

Objectives

- Define transducer.
- Explain how two different types of transducers work.
- Identify the micro equivalent of two macro-sized transducers.

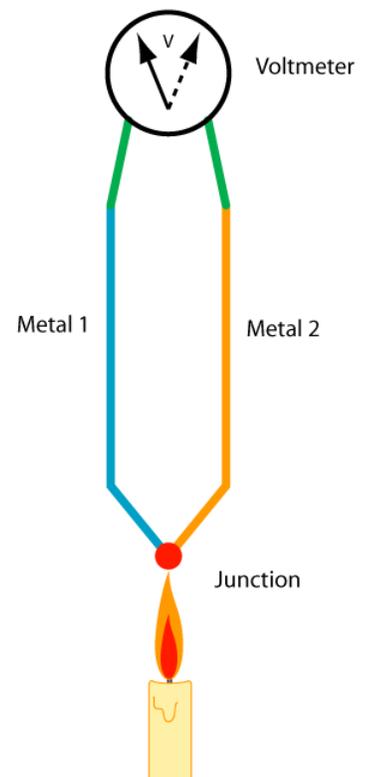
Key Terms (These terms are defined in the glossary at the end of this lesson.)

actuator
electroacoustic
electrochemical
electromagnetic
electromechanical
electrostatic
energy
mechanical
optical
photoelectric
sensors
transducer

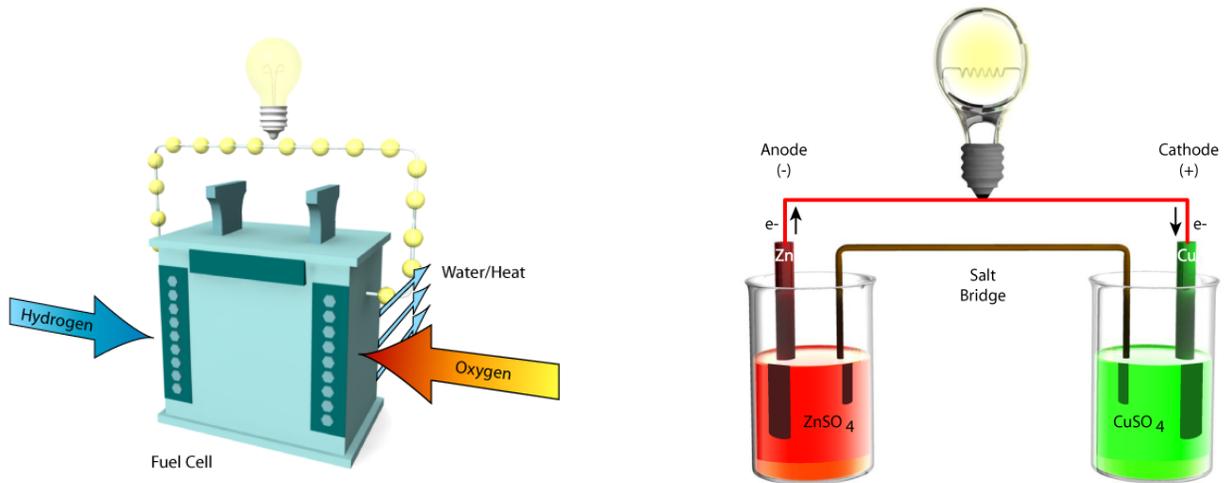
Basic Concepts of Transducers

There are many variables which affect our everyday lives: speed of a car, velocity of the wind, temperature of the oven, light level in the room. In most situations these variables are continuously monitored. It is these variables that are the feedback used to control the speed of a car, oven temperatures, and light levels. The elements that sense these variables and convert them to a different output energy are transducers. Going back to the thermocouple, the thermocouple “senses” an increase or decrease in temperature and outputs a voltage proportional to the change in temperature. This “sensing” element consists of two dissimilar metals joined together at one end into a junction. When the junction of the two metals is heated or cooled, a voltage is produced across the opposite ends of the metals. This effect was discovered by Thomas Seebeck, and thus named the Seebeck Effect or Seebeck coefficient. The voltage produced is representative of the junction temperature. As the junction temperature increases, the voltage increases proportionally and vice versa. This is an energy conversion – temperature (heat energy) to voltage (electrical energy).

In summary, a transducer is a substance or a device that converts an input energy into a different output energy. Because of this broad definition, there are many devices that can be defined as transducers. Such devices come in many varieties converting several different types of energies. Following is a discussion of some of the more common types of transducers.



Electrochemical Transducers



Converting a Chemical Reaction to Electrical Energy (left: Fuel Cell, right: battery)

Electrochemical transducers convert the energy from a chemical change or reaction to electrical energy and vice versa.

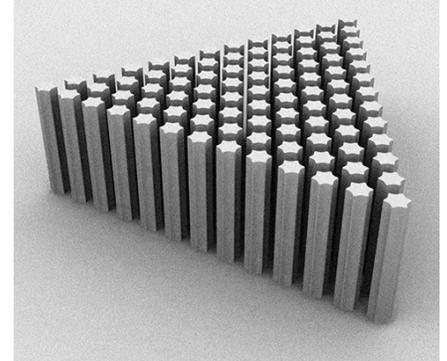
Some common electrochemical transducers include the following:

- pH probe – Converts chemical energy into an electrical energy
- Molecular electric transducer (MET) – Converts motion or convection in an electrolytic solution into electrical energy
- Battery – Converts chemical energy directly into electrical energy
- Fuel cell – Converts the energy from a reaction within the fuel cell between oxygen and a fuel, such as hydrogen, to electrical energy
- Galvanic Cells (also called electric batteries) – converts chemical reactions to electrical energy

Let's take a closer look at the electrochemical battery illustrated above. This battery converts chemical energy directly into electrical energy. A cathode and an anode typically of two dissimilar metals are immersed in an electrolyte solution containing salts of their respective metals. A medium (the salt bridge) separates the two electrodes, but allows ions to flow through the bridge from one solution to the other. Due to the flow of ions between the two solutions a potential difference (or voltage) is created. If a wire is placed connecting the two pieces of metals (the electrodes), current flows. The amount of voltage developed across the cathode and the anode depends on the materials that make up the battery.

The fabrication of micro-sized batteries is a challenge but a challenge that needs to be met. Micro-sized sensors require micro-sized batteries in order to operate, especially when those sensors are placed in remote areas such as the ocean floor or embedded below the surface of bridges and roads.

So how do you get a long-lasting battery from a device that is smaller than the diameter of a strand of hair? “Traditional batteries have a two-dimensional array of positive and negative electrodes stacked on top of one another like sheets of paper. Increasing battery power means adding more electrode layers, more weight and more size.”¹ One solution to creating smaller batteries is to fabricate 3-dimensional microelectrode arrays consisting of high aspect ratio carbon posts (carbon posts that are much taller than they are wide). These posts (between 100 nm to 1 nm in diameter) serve as the electrodes for carbon MEMS batteries.³



This graphic illustrates an array of carbon posts fabricated using a LIGA micromachining process. These posts have an aspect ratio of about 10:1. Imagine these posts at a ratio of 100:1.

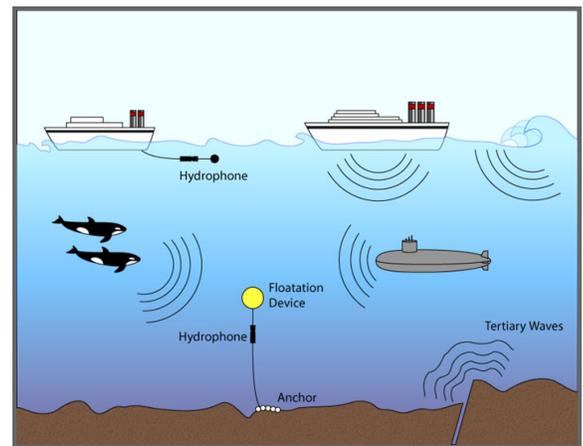
Electroacoustic, Electromagnetic, and Electrostatic Transducers

Electroacoustic transducers work with sound energy and electrical energy.

Common electroacoustic transducers:

- Loudspeaker – Converts an electrical signal into sound
- Microphone – Converts sound waves in air into an electrical signal
- Hydrophone - Converts sound waves in water into an electrical signal.

MEMS hydrophones are currently being used to detect various sounds within our oceans. Anchored to the bottom of the ocean or dragged behind a ship, micro-sized hydrophones detect the sounds generated by ships, submarines, ocean waves and marine animals. They also hear tertiary waves created by earthquakes or any movements within the earth’s crust.⁴



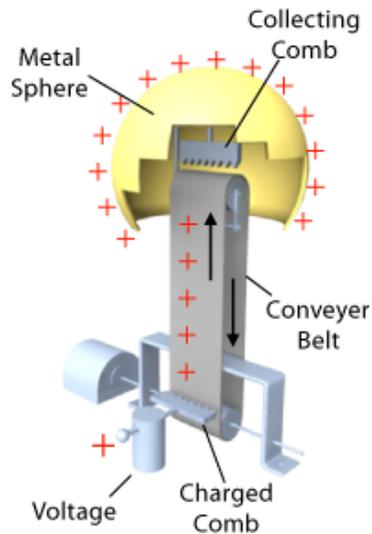
Common electromagnetic transducers:

- Magnetic cartridge – Converts motion in a magnetic field into an electrical energy
- Generator – Converts motion in a magnetic field into electrical energy

An electromagnetically driven and sensed MEMS gyroscope is currently on the market. This gyroscope uses a permanent magnet and a resonating “ring” to detect rotation or motion.⁵

Common electrostatic transducers:

- Electrometer – Converts static or energy from a vibrating reed into electricity
- Van de Graaf generator – Converts static into high voltage (*see figure below*)

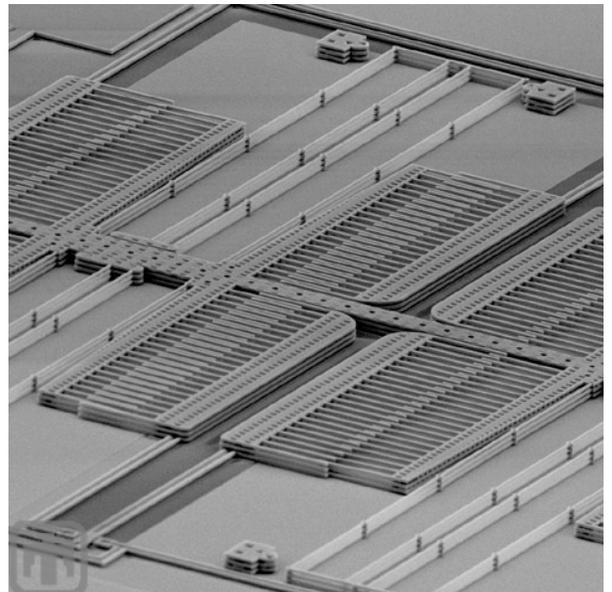


*Van de Graaf Generator:
Converts a built up charge
of static electricity into a
high voltage*

MEMS electrostatic transducers can be found in and are being researched for use in MEMS resonators, on/off valves for fuel injection, and drop ejectors that use an electrostatic driven piston.⁶

A common electrostatic microtransducer is the comb drive. MEMS comb drives are found in both actuators and sensors. Referring to the SEM image below, you can see that a comb drive consists of two interlaced “combs”. One comb is stationary and one moves; one comb is at ground potential and another comb receives a positive voltage. When the voltage is applied, electrons flow from ground to the tips of the comb teeth on the grounded comb.

There is now a positive and negative charge on opposite combs, pulling the moveable comb inward. When the voltage is removed, the moveable comb is returned to its original position by springs that are built into the system. Therefore, as you can see, a comb drive is converting electrostatic energy into movement or mechanical energy. This movement can be used to move something, like a switch or a gear, turning the comb drive into an actuator.



*Scanning Electron Microscope (SEM)
image of a comb drive.*

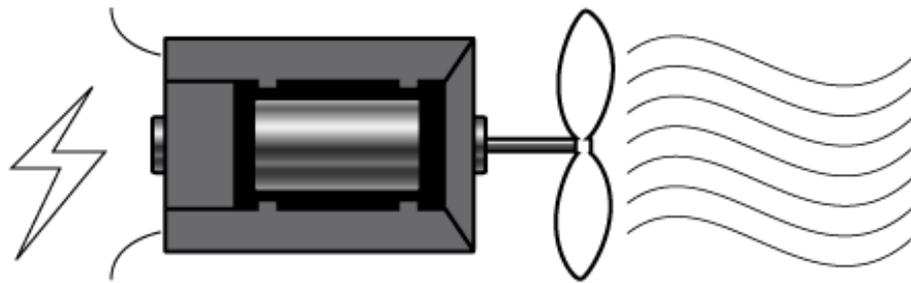
*Courtesy of Sandia National Laboratories, SUMMiT(TM)
Technologies, www.mems.sandia.gov*

Electromechanical Transducers

Electromechanical transducers are transducers that either convert electrical to mechanical energy or motion, or convert mechanical movement such as deformation or stress into electrical energy.

Electromechanical Transducers – (Some are also called actuators)

- Strain gauge – Converts the deformation (strain) of an object into a change in electrical resistance
- Galvanometer – Converts the electric current of a coil in a magnetic field into movement
- Generator – Converts mechanical energy (motion) into electrical energy.
- Motor – Converts electrical energy into mechanical energy (*graphic below*)
- Microaccelerometer – Converts motion or mechanical energy to electrical energy
- Microgyroscope – Converts rotation or tilt (movement) to electrical energy

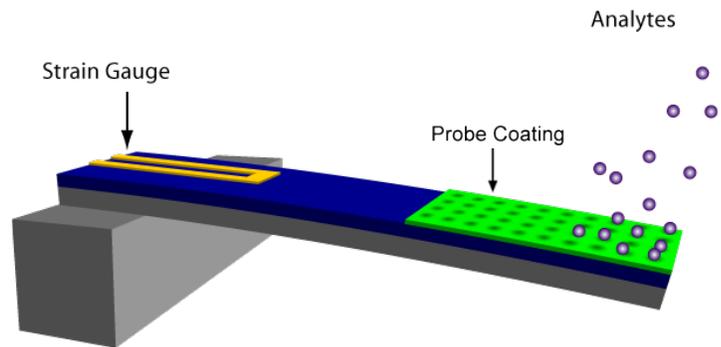


A motor converts electrical energy into mechanical energy

As with other types of transducers, electromechanical transducers come in all sizes from macro to micro. Microgenerators have been developed that may someday replace batteries. A Georgia Tech MEMS Project has developed a 10 millimeters wide generator that spins a micro-sized magnet above a mesh of coils fabricated on a chip. The micromagnet spins at 100,000 rpm, producing 1.1 watts, enough power for a cell phone.⁷

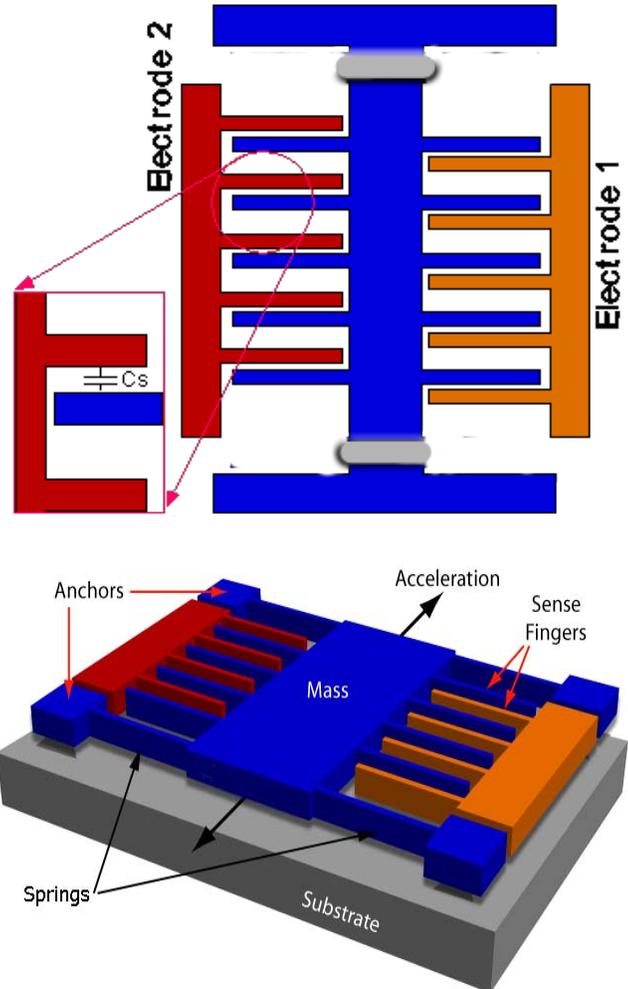
Strain gauges are commonly incorporated into MEMS devices such as pressure sensors and micro-cantilevers. MEMS strain gauges use the piezoelectric properties of metals and other materials to change the resistance of the materials when the strain gauge is “stretched” due to mechanical movement.

This graphic illustrates a micro-cantilever with a strain gauge used to measure an increase in cantilever mass. As the analytes or particles being analyzed attach to the probe coating on the cantilever, the mass of the cantilever increases, causing the cantilever to “bend” and the strain gauge to lengthen. This changes the resistance of the gauge and thus the amount of current flowing through it. This change in current is proportional to the change in cantilever’s mass.

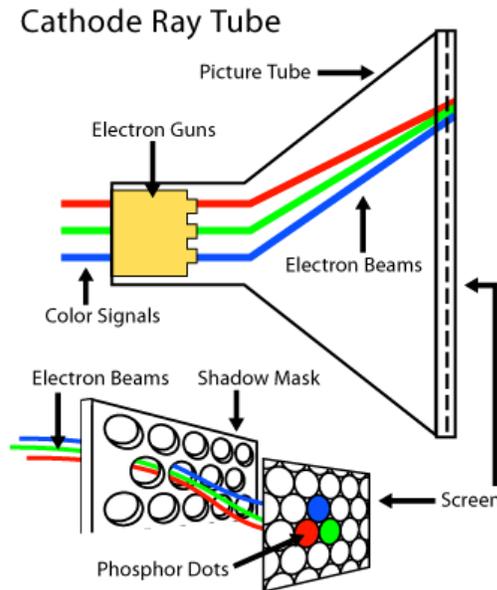


Microaccelerometer

Microaccelerometers are components found in many MEMS inertial sensors. The accelerometer component is a transducer that contains an “inertial mass” (or proof mass) that moves with a change in acceleration. An accelerometer consists of two electrodes – a moveable electrode (the inertial mass) and a fixed electrode. In the class of a in-line accelerometer seen in these graphics, the two electrodes have interlaced “sensing fingers”. One electrode is grounded. The other electrode is connected to a voltage. When a voltage is applied, a capacitance is created between the sensing fingers. When the mass moves due to an external force (or acceleration), the capacitance changes. As a transducer, this accelerometer converts mechanical energy to electrical energy. As a sensor, additional electronic circuitry is used to interpret or quantify the changes in capacitance as proportional changes in acceleration.



Other Types of Transducers



Converts Electrical Signals into Light Energy

Photoelectric Transducers (light to electricity or electricity to light):

- Cathode ray tube (CRT) –Converts electrical signals into light energy for a visual output (*graphic above*)
- Light bulb –Converts electrical energy into visible light and heat (*explained in next section*)
- Laser diode – Converts electrical energy into light energy
- Photodiode - Converts light energy into electrical energy

Thermoelectric Transducers (heat to electricity or electricity to heat):

- Thermocouple – Converts heat energy into electrical energy
- Temperature sensitive resistor (Thermister) – a variable resistor affected by temperature changes (heat energy to electrical energy)

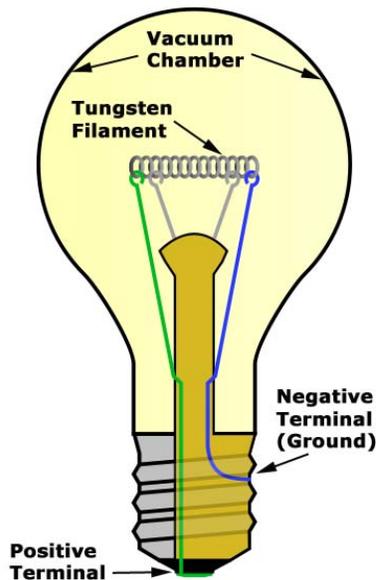
Other types of Transducers:

- Geiger-Müller tube – Converts radioactive energy into electrical energy
- Quartz Crystal – Converts mechanical stress into electricity (electrical energy)

Micro-sized transducers that use temperature, chemical reactions, and mechanical stress to produce changes in voltage, resistance, resonant frequency, or light are used throughout microsensors. Such transducers are used in MEMS pressure sensors, temperature sensors, chemical sensor arrays, and optical modulators.

Let's take another look at the incandescent light bulb, a macro-sized photoelectric transducer and its micro-sized equivalent – the light-emitting diode or LED.

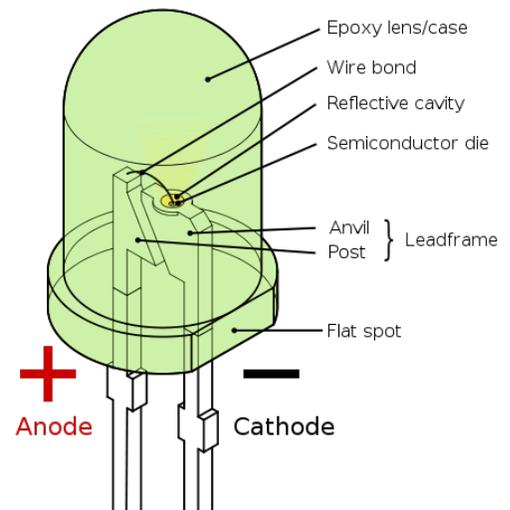
The Incandescent Light Bulb (a transducer)



Schematic of an incandescent light bulb. A power source's positive and negative terminals are connected to the bulb's terminals. An electrical current flows through the filament. The resistance of the tungsten filament converts the electrical energy into heat and light.

Light bulbs convert electrical energy into light and heat. Specifically, an incandescent light bulb consists of a vacuum chamber (the glass bulb), a filament (typically made of tungsten), and a positive and a negative terminal (or contact points) (*see the figure above*). The negative terminal is the part that screws into the socket to prevent electrical shock. A voltage source is placed across the positive and negative terminals causing current to flow through the filament. Due to the electrical resistance of the tungsten filament, the filament heats up and gives off light (i.e., electrical energy, to heat energy, to light energy).

Two micro-sized photoelectric transducers that you are probably familiar with are the solar cell, which converts light energy to electrical energy and the light-emitting diode (LED) that converts electrical energy to light. In a LED, current flowing through the semiconductor die (or diode), causes an emission of photons or light. Both of these devices – the solar cell and LED - are currently being mass produced and are already smaller and more efficient than their predecessors.

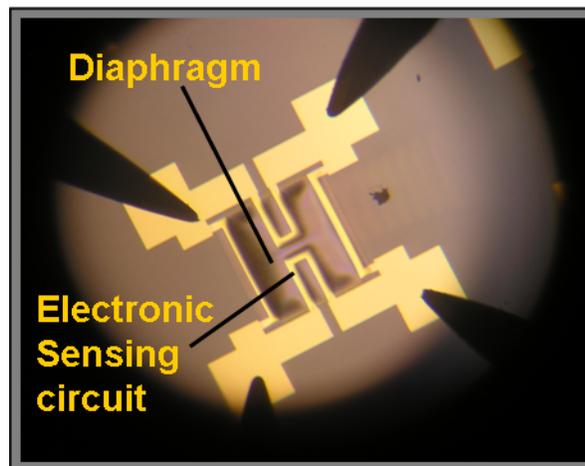


Light-emitting diode with a micro-sized semiconductor die

Summary

A transducer is a device that converts one form of energy into another. Transducers are used in all aspects of life to measure changes in the environment, to enhance everyday applications, and to learn more about the world around us. An actuator is a device that converts energy into motion. Therefore, in some cases, an actuator can also be a transducer. When the output of the transducer is converted to a readable format, the device is called a sensor.

Regardless of the scale, the operation of macro and micro-sized devices remains the same. With all such devices, as the transducing components shrink, so do the components for the output circuitry. The diaphragm micropressure sensor in the picture below is only a few micrometers square. The electronics that communicate with this device are also in the microscale. This allows for a micro-sized package that can be mounted in the smallest of places. Through nanotechnology, we are able to fabricate transducers in the nanoscale. These nanotransducers require nano to microscale components to complete the sensor or actuator.



Example of a Diaphragm MicroPressure Sensor [University of New Mexico, MTTC]

Key Terms

Actuator: A specific type of transducer that converts energy into motion.

Electroacoustic: The interaction between electrical and acoustic phenomena.

Electrochemical: The interconversion of chemical and electric phenomena.

Electromagnetic: Objects made magnetic by an electric current and vice versa.

Electromechanical: Relating to a mechanical device actuated or controlled by electricity.

Electrostatic: Of or related to electric charges at rest or static charges.

Energy: The sources of energy encompass electrical, mechanical, hydraulic, pneumatic, chemical, thermal, gravity, and radiation energy. There are two types of energy---kinetic and potential. Kinetic energy is the force caused by the motion of an object, for example a spinning flywheel. Potential energy is the force stored in an object when it isn't moving, such as a battery.

Mechanical: Pertaining to or concerned with machinery or tools.

Optical: Referring to the behavior and properties of light and the interaction of light with matter.

Photoelectric: Relates to the electrical effects caused by light.

Sensor: A device that responds to a stimulus, such as heat, light, or pressure, and generates a signal that can be measured or interpreted.

Transducer: A substance or device that converts input energy of one form into output energy of another.

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