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

<u>MEMS Fabrication Topic</u>

MEMS Cantilevers Learning Module – Book 1

<u>This booklet contains four (4) Sharable Content Object (SCOs):</u>
Knowledge Probe (Pre-test)
MEMS Cantilever Application Overview
How Does a Cantilever Work?
Chemical Sensor Arrays

Target audiences: High School, Community College.

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants #DUE 0830384 and 0902411.

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MEMS Applications Topic

MEMS Cantilever Applications

Primary Knowledge (PK)
Shareable Content Object (SCO)

This SCO is part of the Learning Module
MEMS Cantilevers

Target audiences: High School, Community College.

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MEMS Cantilever Applications Overview

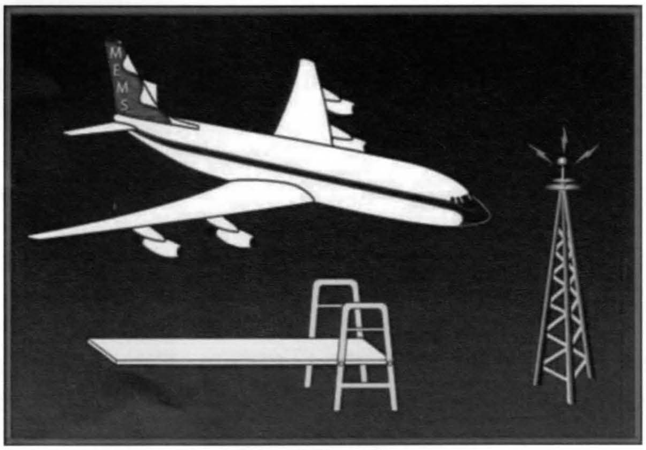
Primary Knowledge
Participant Guide

Description and Estimated Time to Complete

The microcantilever is a widely used component in microsystems devices. Its flexibility and versatility make it a popular component for a variety of applications in a number of fields (e.g., environmental, biomedical, consumer products). This unit discusses several applications of microelectromechanical systems (MEMS) cantilevers and microcantilever-based devices.

Estimated Time to Complete
Allow approximately 30 minutes.

Introduction



Types of Cantilevers

Cantilevers are found throughout the world in applications ranging from aircraft design to architecture and more recently, medical diagnostics, nanoscale measurement systems, and forensics. So what is a cantilever?

A cantilever is a type beam which is supported and constrained at only one end. Based on this description the wings of most aircrafts, balconies of buildings and certain types bridges are cantilevers. Free standing radio towers, anchored to the ground, suspended upwards without cables are also cantilevers. Of course the most familiar cantilever is a diving board.

Cantilevers come in all sizes. The previous examples range in length from a few meters to hundreds of meters. In contrast, MEMS cantilevers can be as thin as a few nanometers with lengths that range from a few microns to several hundred microns. MEMS cantilevers are used in micro transducers, sensors, switches, actuators, resonators, and probes.

This unit discusses some of the more common applications of MEMS cantilevers. For more in depth descriptions of how cantilever-based MEMS work or the theory behind how a cantilever works, refer to SCME Related Units at this end of this unit.

Objectives

- Discuss four different applications in which MEMS cantilevers are used
- Discuss the advantages and limitations of microcantilevers compared to larger cantilevers.

MEMS Cantilever Applications

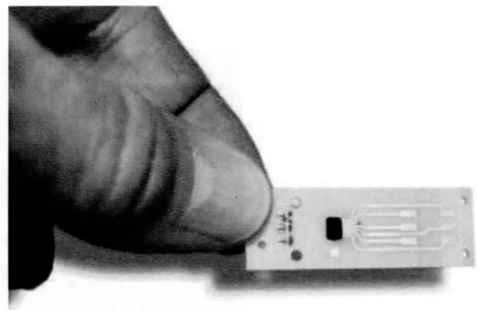
MEMS cantilevers are used as sensors, transducers, probes, needles, transport mechanisms, resonators, latches, switches and relays. They are used

- to detect physical, chemical, and biological particles (target materials) with extremely high sensitivity and selectivity,
- to penetrate tissue in therapeutic and diagnostic applications,
- as tweezers or grippers for pick and place applications of nano-sized particles or microscopic surgeries, and
- as transport mechanisms for sensors to detect nano-size particles on a surface.

The MEMS cantilever in the picture is a silicon based piezo cantilever. The cantilever transducer at the end of the device uses a Wheatstone Bridge design to detect temperature changes. The output of the bridge is transferred via the MEMS electronics (the four lines and contact pads).

Some areas in which cantilever-based MEMS are already being used include the following:

- Biomedical Applications (BioMEMS)
  - Biosensors (antigens, antibodies, PSA, DNA, proteins, viruses and micro-organisms)
  - Diagnostics
  - pH sensors
  - Therapeutics
- Atomic Force Microscopes (AFM)
- Scanning Force Microscope (SFM)
- Read/Write storage devices
- Photothermic spectroscopy
- Environmental Monitoring
- Homeland Security
- Food Production and Safety
- Olfactory Simulation
- RF Switching
- High frequency resonators

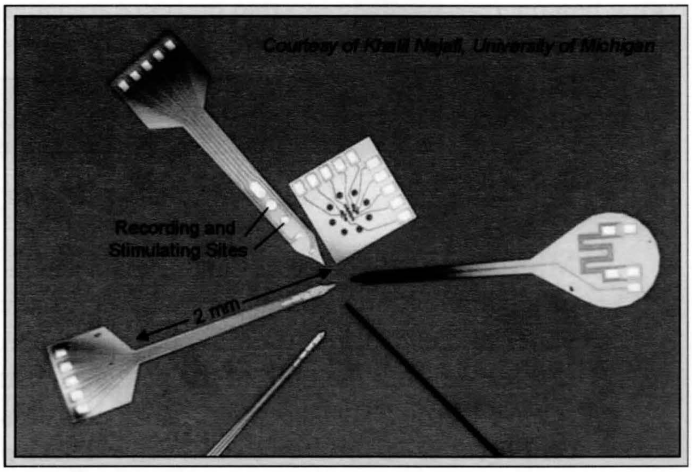


Cantilever sensor (Cantilever Transducers with electronics) [from Lawrence Livermore National Labs]

MEMS Cantilever Fabrication

MEMS cantilevers are fabricated from various materials. The most common materials are silicon (Si, mono- or polycrystalline or amorphous compositions), silicon nitride (SiN) of various stochiometries (the relative amount of silicon to nitrogen atoms which make up the silicon nitride), and polymers. The type of material and the physical dimensions chosen are determined by the cantilever's application and operational requirements.

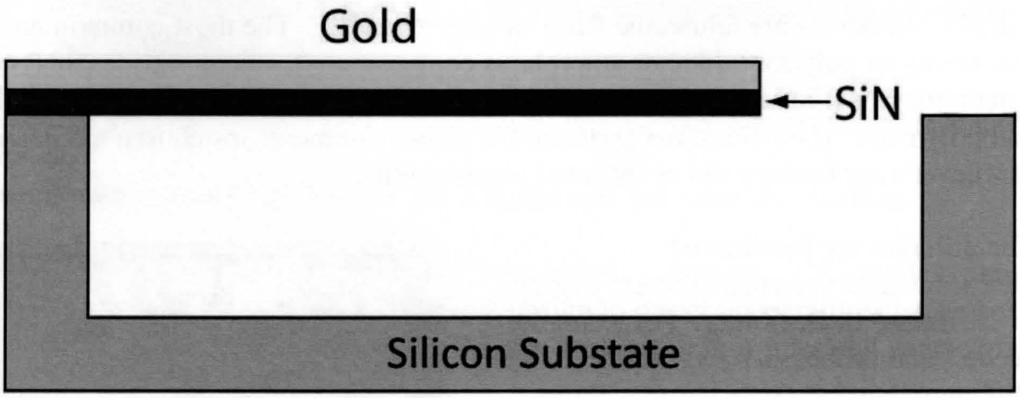
The different applications of microcantilevers require different degrees of "stiffness" or flexibility. For example, needles and probes *(see picture)* need to be stiff enough to penetrate tissue without bending. Resonators, latches and cantilever transport devices need to be stiff enough so as not to oscillate or flex due to weak ambient forces. However, such devices may need certain electrical characteristics not required by biomedical needles. Some cantilever sensors and transducers are fabricated with materials that expand or contract due to chemical reactions or particle interactions.



Probes with MEMS sensors at the probe tips

In addition, cantilevers can be built as single devices or in arrays (as the needle array in the SEM). Therefore, the application of a cantilever determines the materials used, the operating characteristics of the material, and the fabrication methods.

MEMS Cantilevers Fabrication Methods



Cantilever Beam released from Silicon (Bulk micromachining)

MEMS cantilevers are commonly fabricated using bulk micromachining, surface micromachining, or a combination of both. In each micromachining process, a solid structure is released from the wafer to create a free-standing beam, anchored at one end. In bulk micromachining the cantilever is released from the bulk of the wafer's substrate. In surface micromachining the cantilever is released from a surface layer. Both micromachining processes allow for the fabrication of a single cantilever or an array of cantilevers. These processes also allow for fabrication and integration of the electronic circuitry and other MEMS components required to interface with the cantilevers.

MEMS Cantilever Characteristics

MEMS cantilevers' presence is expanding into a variety of applications. This popularity is due several characteristics which include the following:

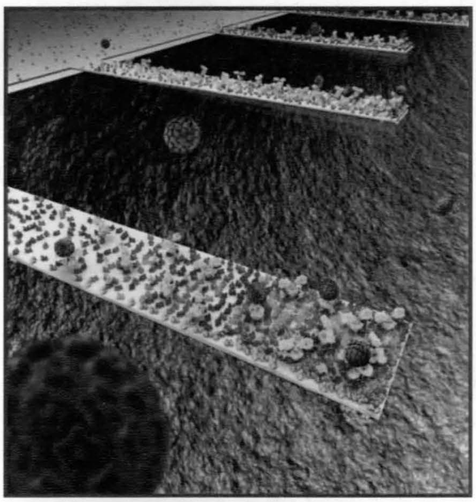
- Ability to render measurable mechanical responses quickly and directly
- Sensitivity to a miniscule amount of external force or stimuli
- Low power consumption
- Capability to fabricate a high density array with simultaneous responses to different stimuli

The simplicity of the basic cantilever as well as its relatively long history in small device applications makes it a key device to study.

MEMS Cantilevers as Transducers

Microcantilever transducers are the most versatile applications of MEMS as well as NEMS (Nanoelectromechanical Systems). MEMS sensors incorporate cantilever transducers with dimensions in the micro or nano-range. Their minute size allows them to interface with integrated circuits on the same chip in order to provide analysis and feedback.

Microcantilevers that are used to sense the presence of a certain particle or analyte are coated with a chemically sensitive material. This material needs to provide for a high degree of specificity in detecting certain particles or "analytes" within a sample. In some biomedical applications, biomolecules may be used as the cantilever coating so that they can better detect specific analytes within a small blood sample. This graphic below is an example of application.



Nanocantilevers coated with antibodies (blue-green) that capture viruses (red spheres). As the cantilevers identify and capture more virus molecules, one or more of the mechanical or electrical characteristics of the cantilevers can change and be detected by an electronic interface.*

The size of the particle being detected and captured is one of the factors affecting the size of the cantilever. [Image generated and printed with permission by Seyet, LLC]

**Antibodies are proteins produced in the blood in response to the presence of an antigen (e.g., virus, bacteria, toxin).*

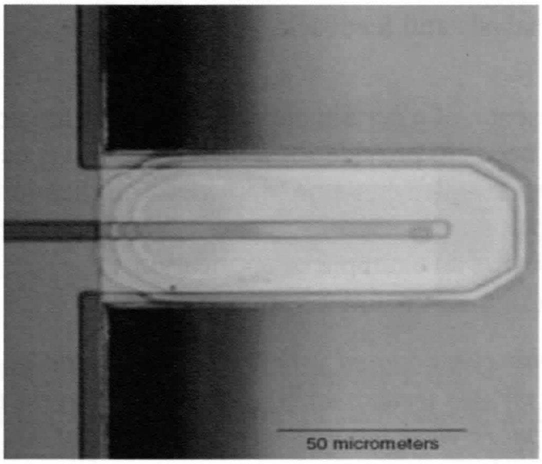
As transducers, microcantilevers rely on their flexibility or elasticity to create some type of measurable change when exposed to external stimuli. The cantilever's reaction to an external stimulus is referred to as mechanical stress. This stress results in a change in one of the cantilever's mechanical or electrical properties. The most common properties used to measure this change are the cantilever's

- natural resonant frequency,
- angular deflection, or
- resistivity.

A discussion on how these properties are used can be found in the SCME unit "How Does a Cantilever Work?"

Examples of Microcantilevers in Sensors

Microcantilevers are fabricated as a single device (i.e., a probe or needle – left image) or as several devices arranged in a sensor array. (right image) Applications for cantilever-based sensor arrays are endless. Following are some of the current applications for cantilever-based sensors.



Single MEMS probe
[Image source: Lawrence Livermore National Labs]

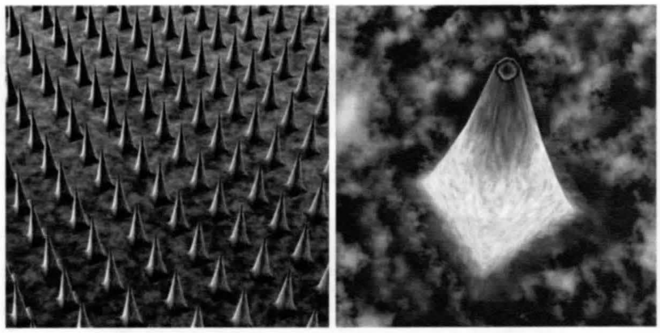
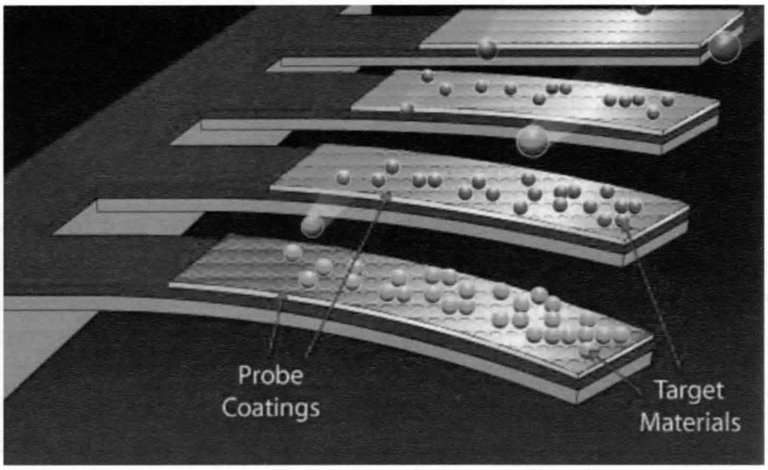


Illustration of a MEMS Needles array with close-up of a needle's tip

Chemical Sensor Arrays (CSA)

A chemical sensor array (CSA) is designed to detect and measure the amount or concentration of one or more substances within a given sample or environment. For example, a CSA used in the medical field identifies the amount of a specific antibody or antibodies with a small blood sample.

CSAs are built to be chemically discriminating. This means that a CSA can be designed with an individual cantilever or a set of cantilevers within the array able to detect one and only one analyte within the sample. The same array can have numerous discriminating cantilevers allowing for the detection of several different analytes within the same sample as shown in the figure below. The different colors of target materials indicate different analytes. The probe coating of each cantilever is designed to bond with only one specific analyte.



A CSA with Discriminating Cantilever Coatings

An artificial nose is an example of a CSA. Each cantilever transducer in an artificial nose is designed for pattern recognition of a specific odor. The artificial nose is used as a recognition tool to identify certain vapors and their concentration with a sample or space. One could think of them as being the MEMS version of a bloodhound.

For more on CSAs, see the unit on "Chemical Sensor Arrays".

Applications of Microcantilever Sensors and Sensor Arrays

- Gas leak detectors (automobiles, airplanes, space shuttles and the space station)
- Detection and characterization of chemicals in liquid and gaseous states
- Biosensors (detect and measure antibodies, protein, enzymes, antigens, and DNA)
- Sensors for DNA hybridization and Protein binding
- pH sensors
- Glucose sensors
- Biomolecular analysis
- Charged-particle flux detector
- Various volatile organic compounds

Advantages of Cantilever Sensors

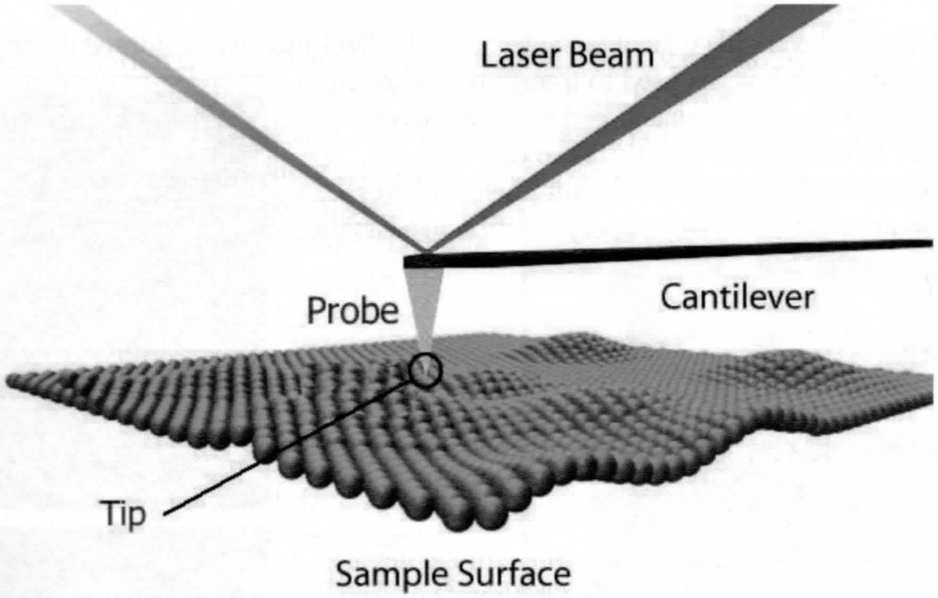
There are several advantages to using microcantilevers in sensors:

- Microscale size
- Ease of constructing many cantilevers in one array
- Ability to detect multiple analytes in one solution using one MEMS device
- Extremely high sensitivity
- Extremely high selectivity
- Flexibility of its working environment (air, vacuum, liquid)
- Wide dynamic range
- Low power consumption

Microcantilevers as Transport Devices

As transducers, microcantilevers need some degree of flexibility in order to "bend" when exposed to its target. As a transport device, a microcantilever needs a higher degree of stiffness. However, for some transport applications, such as the Atomic Force Microscope (AFM) cantilever, some "bending capability" is still required. Following are examples of three applications for cantilevers used as transport devices.

Cantilevers as Transport Devices: The AFM



AFM Cantilever and Tip

An Atomic Force Microscopes (AFMs) is a cantilever-based MEMS. It is a high-resolution scanning probe microscope with demonstrated resolutions in fractions of a nanometer. An AFM provides a three-dimensional profile of the surface being scanned.

In an atomic force microscope the cantilever is used to transport a ceramic or semiconductor probe constructed on the suspended end of the cantilever. *(Refer to the figure of the AFM Cantilever and Tip)* One type of AFM deflects a laser off the top of the cantilever. As the tip interacts with the sample surface, it experiences forces that repel or attract it to the sample. The electronics of the AFM are designed to maintain a constant force between the surface and the tip so that the probe moves in a parallel path relative to the sample surface.

As the cantilever probe moves in a constant parallel path above the sample's surface, the cantilever is pushed and pulled up and down mirroring the path of the tip. This interaction bends the extended portion of the cantilever causing a change in the angular deflection of the laser on the cantilever's surface. These changes are detected and translated as variations in vertical distances on the sample's surface.

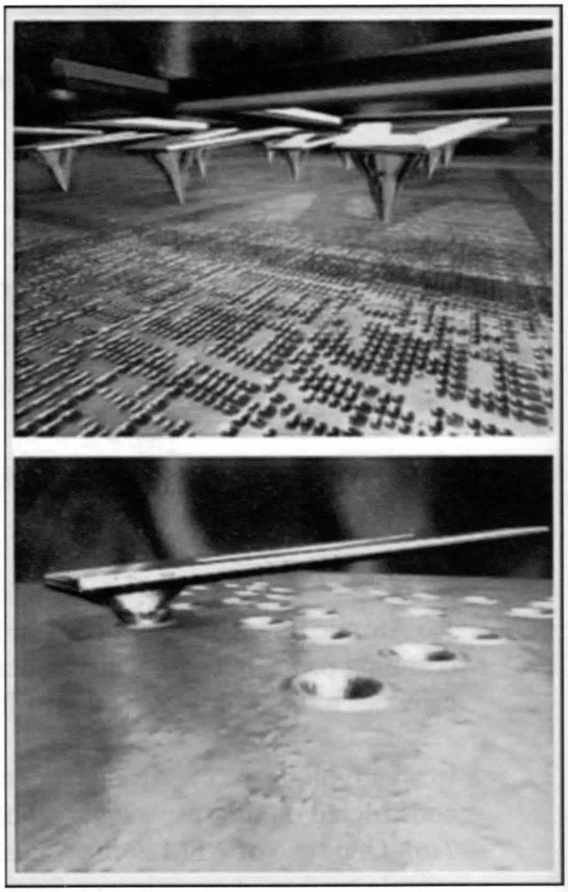
(*For more information on AFMs, see the SCME unit on Atomic Force Microscopes.)*

Cantilevers as Transport Devices: Read/write storage

MEMS cantilevers have been considered for MEMS read/write storage devices. In storage devices, the MEMS cantilever is used to transport a probe tip constructed on the suspended end of a cantilever (similar to that in the AFM). These tips have a diameter of approximately 10 nm. The cantilever and tip are suspended over a polymer film used as the storage medium.

The tips detect (read) the presence or absence of matter in the polymer film (0 data bit or 1 data bit). They also move or displace matter (write) a few nanometers in width (create a bit or erase a bit). *(See figure of IBM Millipede)*

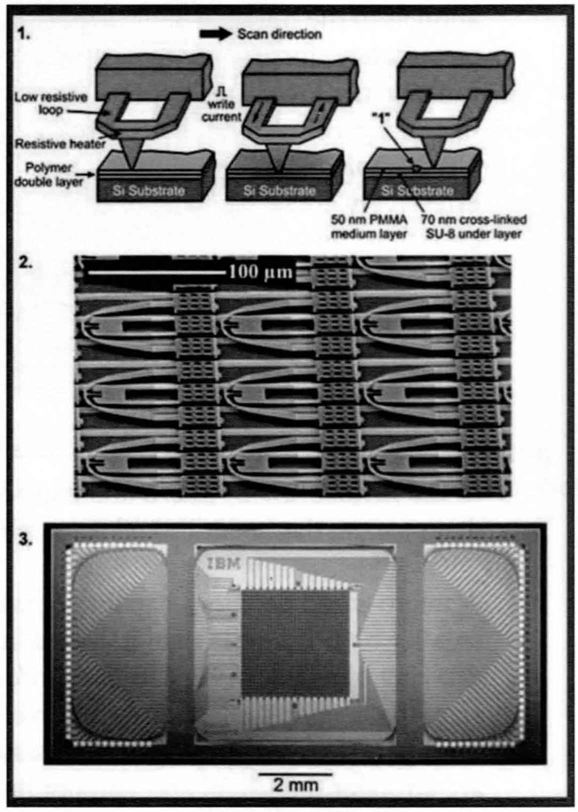
It is projected that MEMS read/write storage devices will be able to store 1 Tbit/in^2 (1 Gbit/mm^2) of data in a unit the size of a postage stamp. This technology is ideally suited for use in mobile devices such as digital cameras, cell phones and USB sticks. Other possible applications include lithography on the nanometer scale, as well as atomic and molecular manipulation.[2] However, even though several prototypes of this device have been made, such devices are still not commercially available. Following is a brief discussion of the IBM Millipede Prototype.



IBM Millipede - Close-up of read/write cantilevers[3]
[Photo courtesy of IBM]

IBM Millipede Prototype

IBM researchers in Zurich have built a parallel, ultra-dense read/write storage device prototype. *(See figure of the IBM Prototype).* This device consists of a microcantilever array positioned over a storage medium made of a polymer film (2). The most recent prototype (2005) consists of a 64 x 64 array of 4,096 cantilevers providing a terabyte of storage on a single chip.[2] The end of each cantilever has a probe tip one micrometer in length and 10 nanometers wide at the apex (1). An electromagnetic actuation precisely moves the storage medium in the x-y directions. Each probe tip reads and writes to a storage area of 100 μm x 100 μm.[3]



IBM Prototype (32 x 32 array)[5]
[Photo courtesy of IBM]

Each cantilever consists of a micro-sized sensor for reading and a heating resistor in the probe tip for writing. To write data, the probe tips are heated and pressed into the surface of the polymer film creating an indention or data bit a few nanometers in size. To read data, the reading sensor in the cantilever is slightly heated. As the storage medium moves under the cantilever, the tip moves in and out of data indentions. As the tip moves into an indention (a data bit), the temperature of the sensor decreases due to a higher surface area between the tip and the polymer surface. The decreased temperature is sensed as a corresponding resistance change and thus, a 1 or data bit.[3]

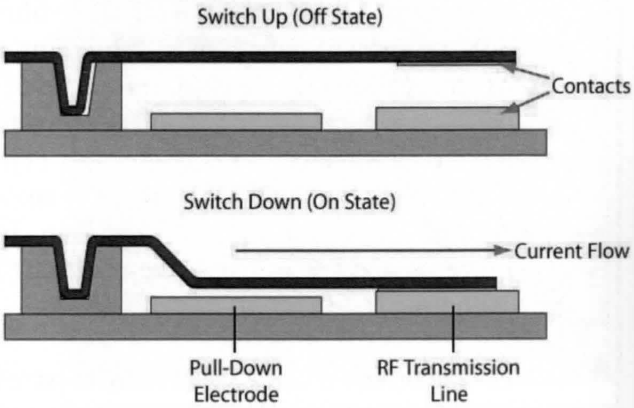
MEMS Cantilevers as Switches

MEMS switches are typically broadband switches meaning that they can operate over a wide frequency range. In theory, MEMS RF switches direct and control signals as high as 50 GHz and possibly higher. Because of their low power consumption, MEMS switches significantly increase the battery life of many handheld applications such as cell phones and PDAs.

MEMS switches are widely used in RF applications. Due to their size, low power consumption, faster switching speeds, higher linearity, and versatility, MEMS switches are replacing electromechanical relay devices as well as solid-state devices.

A MEMS RF Switch

A MEMS RF switch (*refer to figure)* is typically a metal cantilever or non-metal cantilever with a metal tip (used as a contact). The end of the cantilever floats above an electrode or contact or both. The distance between the two contacts is usually 1 to 3 micrometers. When a voltage is applied to the pull-down electrode, the resultant electrostatic force pulls the cantilever contact towards the lower contact (RF Transmission line in figure) until the two come together. Upon contact, the switch is closed. This contact effectively creates a short circuit, allowing current to flow.

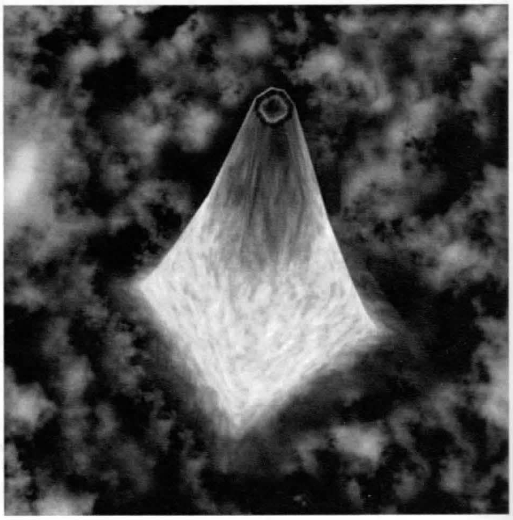


MEMS RF Switch

Microcantilevers as Needles

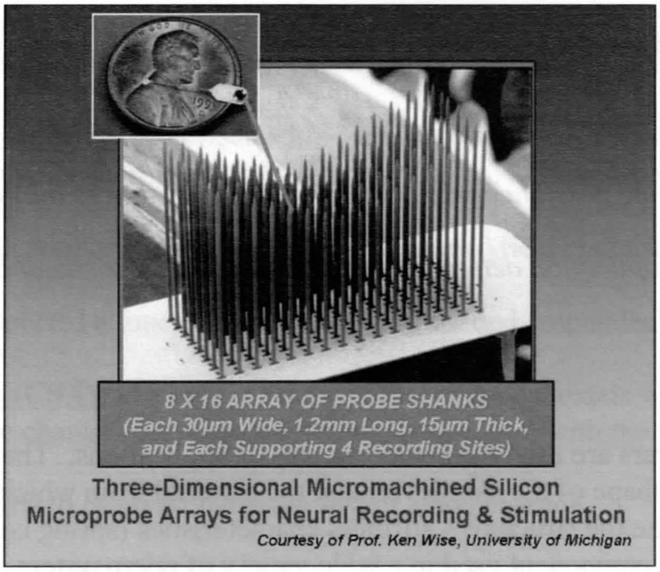
In the medical field, micro and nano-sized cantilevers are being used as needles and as probes for diagnostics, therapeutics and research.

A micro-sized needle is capable of taking a much smaller blood sample than its macro-equivalent by drawing blood flow via capillary force. Because of its size, the needle's injection is relatively painless and even pain-free, depending on the subject. Such needles are stronger than steel and will not break when penetrating tissue.



Micro and nano-sized needles are used singly and in needle-arrays for drug delivery applications. The image to the right illustrates a microneedle which can be made with silicon. Such needles can be as small as 40 μm in diameter and 500 μm tall.

Microcantilevers as Probes

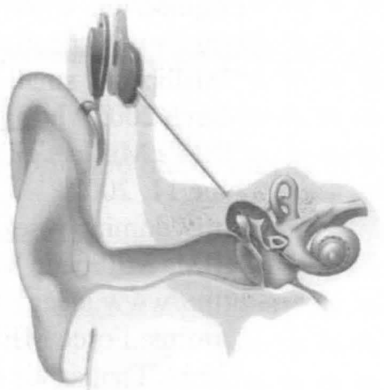


Three-Dimensional Micromachined Silicon Microprobe Arrays for Neural Recording & Stimulation
Courtesy of Prof. Ken Wise, University of Michigan

Diseases such as Parkinson's disease and Alzheimer's have helped to mobilize research into using micro and nano-sized cantilevers and cantilever arrays as neural probes *(see figure)*. Neural probes and neural probe arrays are being developed for a variety of applications:

- Studying the brain network
- Studying the central and peripheral nervous system
- Treating of Neurological disease through the use of neural prostheses

Neuroprosthetic devices are already being used successfully to alleviate the symptoms due to Parkinson's disease and deafness. For Parkinson's disease, neuroprosthetics are implanted deep into the patient's brain to enable deep brain stimulation. For the hearing impaired, a Cochlear implant is a neuroprosthetic that allows a deaf person to hear noises never heard before. *(See diagram of Cochlear Implant)* A neural probe can be designed to provide recording and stimulation of specific sites in the nervous system restoring function that was lost due to disease or trauma. Neuroprosthetic devices have become one of the most important emerging technologies in biomedical engineering applications.



Cochlear Implant
[Image courtesy of National Institute of Health]

Food For Thought

1. *How are macro-sized cantilevers similar to micro-sized cantilevers?*
2. *How are they different?*
3. *What are some possible applications for microcantilevers that were not discussed?*
4. *How does application determine the stiffness characteristic of the cantilever?*

Summary

MEMS cantilevers are used for a wide variety of applications. The specific application defines the best geometric shape of the cantilever, and the material from which it should be made. These two parameters define the structure's stiffness characteristics (spring constant). The MEMS cantilever is a cornerstone component used in a wide variety of microsystems including micro-chemical sensor arrays, atomic force microscopes, microswitches, and neural probes.

References

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3. "IBM's Millipede Project Demonstrates Trillion-bit Storage Density". IBM Research. Zurich. June 11, 2002. http://domino.research.ibm.com/comm/pr.nsf/pages/news.20020611_millipede.html
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6. Microneedle array image: Fabricated by Professor Kazuo SATO, Professor, Department of Micro-Nano Systems Engineering, and Director, Center for Creative Engineering, Graduate School of Engineering, Nagoya University
7. Neural Probe: http://helios.snu.ac.kr/sub_02-eng.html

Glossary

Analyte: A substance or chemical constituent that is undergoing analysis or being measured.

Atomic Force Microscopes (AFM): A device for mapping surface atomic structures by measuring the force acting on the tip of a sharply pointed object that is moved over the surface.

BioMEMS: MEMS with applications for the biological / analytical chemistry market.

Cantilever: A beam supported at one end and with the other end suspended freely outwards.

Chemical Sensor Arrays (CSA): An array of sensors that chemical reacts with a target material resulting in a measurable change (i.e. resonant frequency or mass) with the sensor.

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

MEMS: Micro-Electro Mechanical Systems – microscopic devices such as sensors and actuators, normally fabricated on silicon wafers.

Resonant Frequency: The frequency at which a moving member or a circuit has a maximum output for a given input.

Resonators: A device or system that exhibits resonance or resonant behavior.

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 form.

SCME Related Units

- How Does a Cantilever Work?
- Chemical Sensor Arrays
- Atomic Force Microscopes
- Cantilever Inquiry Activities I and II
- Cantilever Activity: Resonant Frequency vs. Mass

Disclaimer

Unit Evaluation

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

To provide feedback, please visit http://scme-nm.org . Click on SCO Feedback.

Your feedback is greatly appreciated.

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MEMS Applications Topic

How Does a Cantilever Work?

Primary Knowledge (PK)
Shareable Content Object (SCO)

This SCO is part of the Learning Module
MEMS Cantilevers

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How Does a Cantilever Work?

Primary Knowledge
MEMS Cantilever Learning Module
Participant Guide

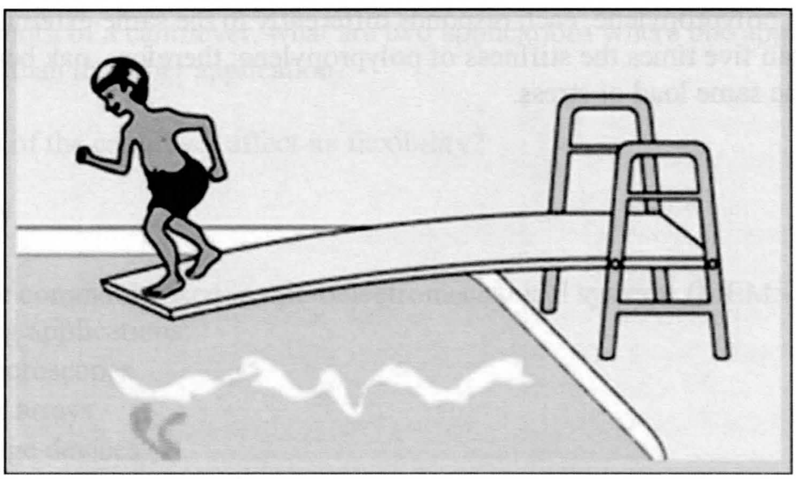
Description and Estimated Time to Complete

The microcantilever is a widely used component in microsystems devices. Its flexibility and versatility make it a popular component for a variety of applications. This unit provides information on the basic characteristics of cantilevers and how these characteristics affect the operational characteristics of macro and microcantilevers.

Estimated Time to Complete
Allow approximately 30 minutes

Introduction

A cantilever is a type of beam constrained at one end with the other end extending freely outwards. In most macroapplications, the cantilever is rigid for minimal movement. No one wants to see a jet's wings flapping or feel a balcony bend when walking out to the end. However, a diving board needs to flex under a load; therefore, it is designed for more flexibility.



In microapplications, some cantilevers are rigid allowing for a controlled movement. Other cantilevers are more flexible allowing for variable degrees of movements. Flexible microcantilevers are used in applications where an external force or intrinsic stress causes the cantilever to flex or bend (e.g. atomic force microscopes, diagnostic transducers, chemical sensor arrays). More rigid cantilevers are used as needles, probes, or transport mechanisms for probes or transducers.

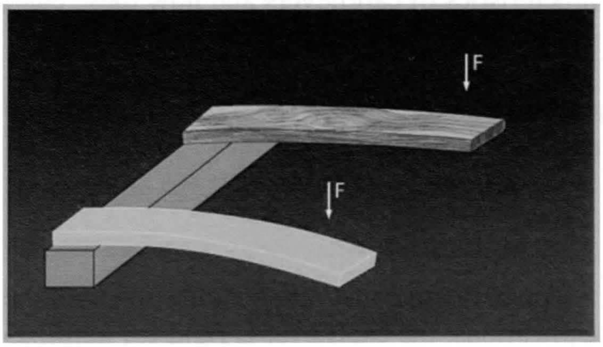
This unit covers the theory of how a cantilever works. It will identify differences in the operation of macro and microcantilevers.

Objectives

- Discuss the static mode of operation for microcantilevers.
- Discuss the dynamic mode of operation for microcantilevers.
- Discuss the differences in the operation of macrocantilevers and microcantilevers.

Cantilever Properties

Several factors affect if and how a cantilever moves or how it responds to external stimuli. Such factors include its dimensions (length, width, thickness) and the properties of the material from which it is made. The geometric shape, as well as the material used to build the cantilever determines the cantilever's stiffness (how it responds when a force is applied).

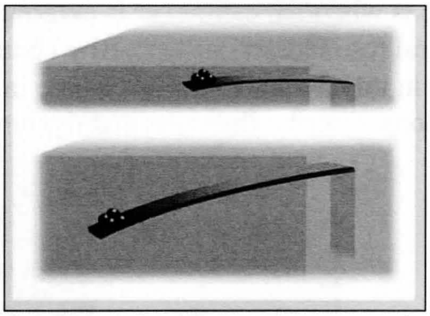


Comparison in the bending of wood and polypropylene cantilevers under the same load (F)

In reference to the material, if one cantilever is made of oak and another with the same dimensions is made of polypropylene, each responds differently to the same external force *(see figure).* Oak has more than five times the stiffness of polypropylene; therefore, oak bends less than polypropylene under the same load or stress.

A Cantilever's Dimensions

For a simple rectangular cantilever, the thickness, length, and width of the beam determine the geometric shape. Each of these parameters affects how a cantilever moves and bends. For example, a short cantilever is stiffer than a long cantilever of the same material, width and thickness *(see figure below.*



A short cantilever vs. a long cantilever

In macroapplications, short cantilevers are used for balconies and longer cantilevers are used for diving boards. In microapplications, a short cantilever (~ 10 microns) works best as a latch or a needle. A longer cantilever (~100 microns) works best as a transducer or sensor. However, there are applications where a long cantilever (e.g. a 1.2 mm neural probe) requires the same rigidity as a 10 micron needle. In this case, the other cantilever dimensions (width, thickness) and possibly the material would be adjusted to provide the rigidity needed.

Questions

In reference to the width of a cantilever, what are two applications where one application requires a *narrower* cantilever than the other application?

How does the width of the cantilever affect its flexibility?

MEMS Cantilevers

Microcantilevers are commonly used in microelectromechanical systems (MEMS). Such systems include the following applications:

- Atomic force microscopes
- Chemical sensor arrays
- Read/write storage devices
- Olfactory systems
- Environmental Monitoring
- RF switches

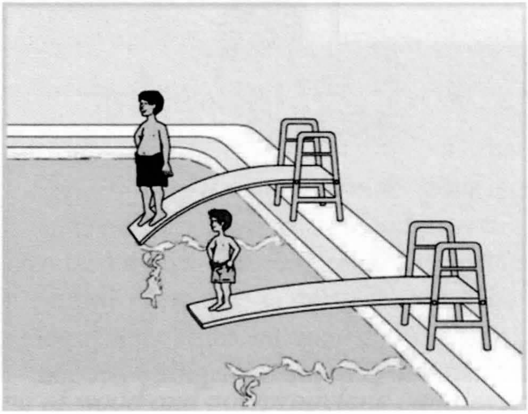
Microcantilever Modes of Operation

Several of these MEMS applications operate the cantilever in either a static mode or operation or a dynamic mode of operation.

- The static mode is when the cantilever is in a static state (stationary). Any displacement of the cantilever due to a load or intrinsic stress generated on or within the cantilever is measured.
- The dynamic mode is when the cantilever is externally actuated causing the cantilever to oscillate at its natural resonant frequency. Any change in the load or mass of the cantilever results in a change in this frequency. The change in frequency is measured.

The following discussions describe the static and dynamic modes of operation for microcantilevers.

Static Mode



Macrocantilever (diving board) bending under load conditions

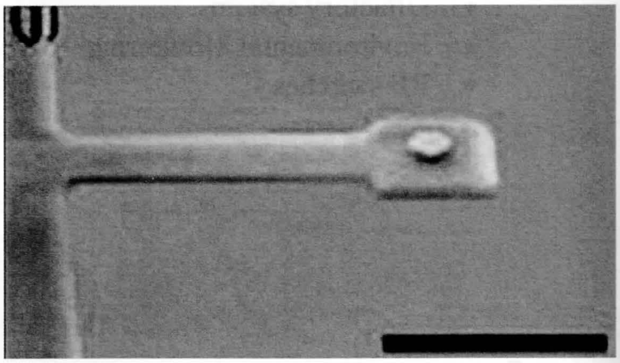
In the static mode, a change in the cantilever's z-displacement indicates a change in load or intrinsic stress. In marocantilevers this displacement is usually due to an external load. Take for instance the diving board. An 80 pound child would cause a small displacement at the end of the diving board compared to the child's 175 pound father. The heavier the load (in this case – a person), the greater the displacement or z-bend.

In microapplications this displacement is due to one of two factors:

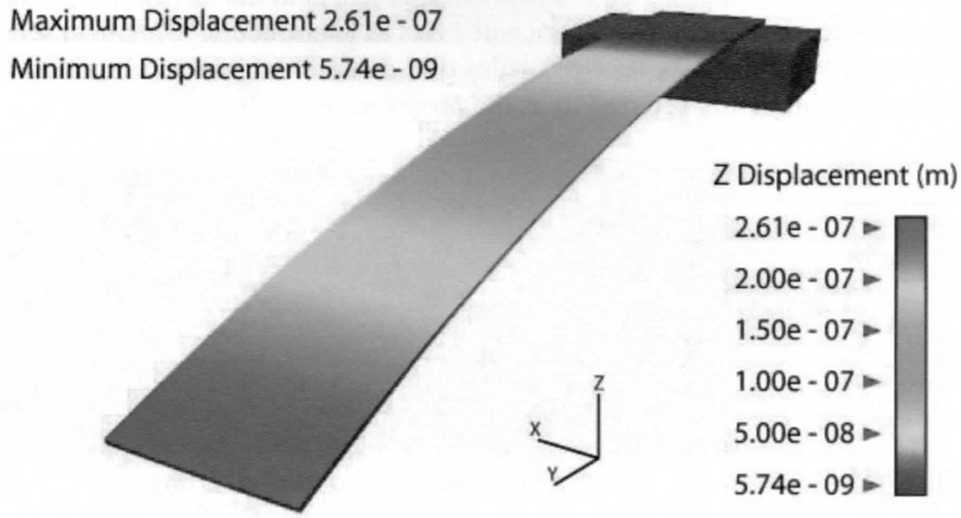
- An external load or force (i.e. Atomic Force Microscopes)
- An intrinsic stress (i.e. chemical sensors and transducers)

Displacement caused by either an external load or an intrinsic stress would normally be considered negligible in the macroscopic world; however, in the micro and nanoscopic worlds, the displacement is large enough to indicate a change in mass as small as a few nanograms or a surface stress of several 10^{-3} N/m (as indicated in the following image). [1]

A gold dot, about 50 nanometers in diameter, fused to the end of a cantilevered oscillator about 4 micrometers long. A one-molecule-thick layer of a sulfur-containing chemical deposited on the gold adds a mass of about 6 attograms, which is more than enough to measure. [Image courtesy of Craighead Group/Cornell University]



Measuring Static Displacement

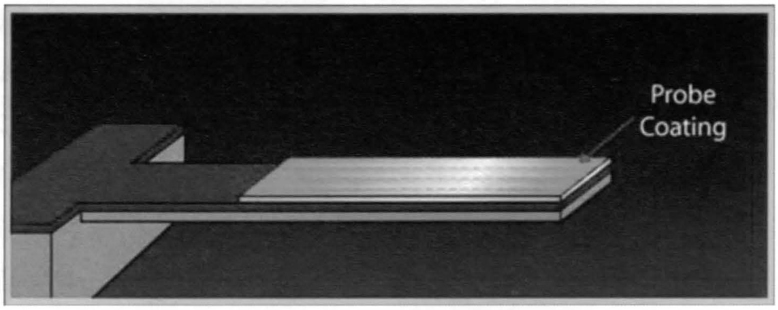


A finite element analysis (FEA) model showing Microcantilever Displacement under Stress

The static mode of operation measures the amount of cantilever displacement. The finite element analysis (FEA) model "*Microcantilever Displacement under Stress*" illustrates the displacement of a microcantilever due to a thermal stress on the cantilever's surface. As shown, z-displacement occurs along the full length of the cantilever. The maximum displacement (only 255 nm) occurs at the suspended end. This is more than enough of a displacement to be measured in the microscopic world. Nanotechnology has enabled the design and fabrication of nanocantilever sensors capable of measuring even smaller displacements (e.g. a 10 nm displacement due to a surface stress of several 10^{-3} N/m). [Lang]

Microcantilevers as Chemical Sensors

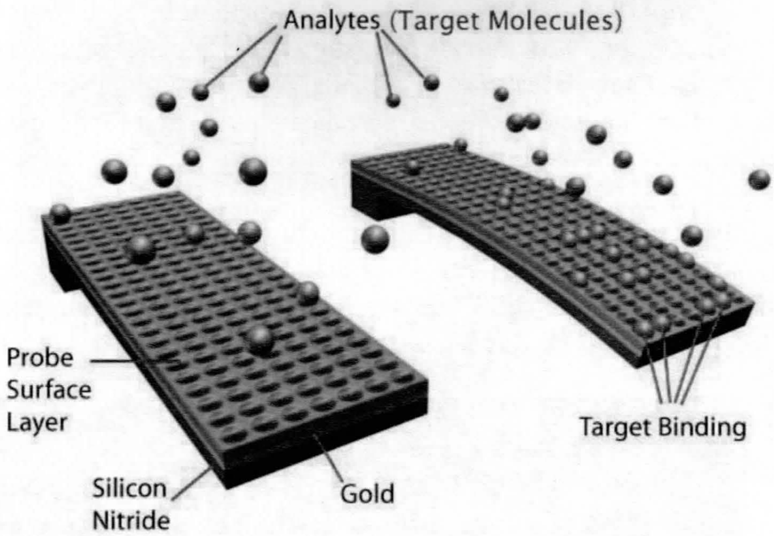
One of the primary applications of microcantilevers is in the environmental and biomedical fields. Chemical sensors incorporate microcantilevers as transducers. Chemical sensors detect, analyze, and measure specific particles (molecules or atoms) within gas and liquid environments. These particles are commonly referred to as the *target material* or *analytes.*



Probe Coating on a Cantilever Transducer

In order to detect a specific analyte, the microcantilever transducer is fabricated with a probe coating (*see figure)* on one surface for static operation or both surfaces for dynamic operation. The probe coating is a chemically sensitive layer that provides specificity for molecular recognition. As the analytes are adsorbed by the probe coating, the transducer experiences surface stress or an overall change in mass which results in cantilever displacement (static) or a change in cantilever oscillations (dynamic). Different coatings provide different chemical reactions. Following is a discussion of different chemical reactions that can occur with microcantilever transducers.

Surface Reaction



Surface Reaction between Analytes and Probe Coating Molecules

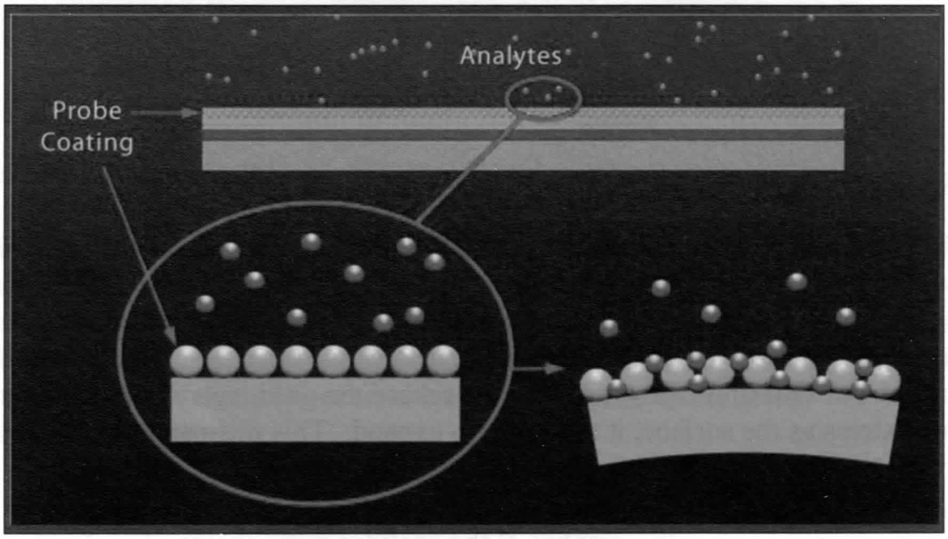
Surface reaction is when the analytes are confined to the surface of the probe coating. The figure shows the probe coating as a monolayer of probe molecules attached to a gold layer of the cantilever. The reaction is chemisorption of the analytes on the cantilever's surface (the probe molecules). Notice how the analytes are confined to the surface. The reaction at the surface causes thermal expansion of the probe coating. Because the gold layer is not experiencing the same thermal stress as the surface, it tends not to expand. This mismatch results in a bending of the cantilever.

In our microcantilever in the graphic, if the analytes were chains of molecules, the thermal stress on the cantilever surface would be greater. This would result in more expansion and a greater *bend* in the cantilever.

Gravity is not a Factor

In the previous figure of surface reactions, it appears that the cantilever is bending just like a diving board bends with weight. However, it is important to note that microcantilevers are not affected by gravitational force. Their deflections are related to asymmetric expansion or contraction of the layers caused by the chemical reactions with the analytes and the probe coating. These reactions generate mechanical stress within the cantilever.

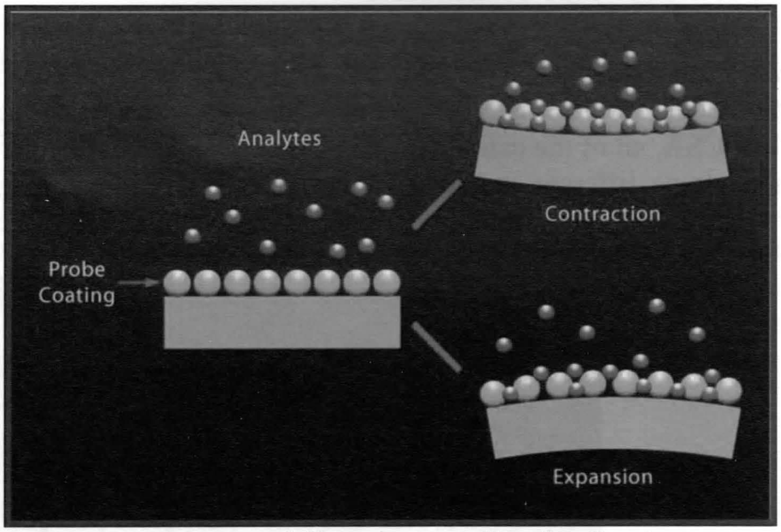
An example of this mechanical stress is the reaction of two different metal strips bonded together and heated. Each metal has a different coefficient of thermal expansion. When heated, one metal expands more than the other. Since they are bonded together, this difference in expansion causes the bonded strip to bend. The direction it bends depends on which metal expands the most.



Expansion of dissimilar layers

In microcantilevers, two different layers (i.e. a probe layer bonded to a gold layer) will not react in the same manner. The figure ("Expansion of dissimilar layers") shows a probe coating on top of a gold layer. The thermally induced stress caused by the reaction between the analytes and the probe coating results in different rates of expansion and a bending of the cantilever.

Molecular Sponge

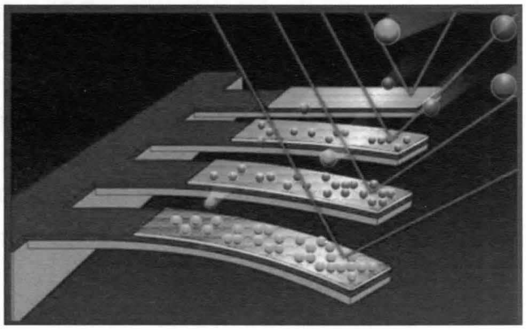


Expansion and Contraction of Probe Coating

In microcantilevers, surface reaction (analytes being adsorbed at the surface) is not the only reaction that can take place. Analytes can also be adsorbed into the bulk of the probe coating, much like the adsorption of water into a sponge. As with surface reaction, if the reaction between the coating and the analytes causes the coating to contract, then the cantilever bends upward. If the coating material expands due to the reaction, then the cantilever bends downward (*as illustrated in the figure – "Expansion and Contraction of Probe Coating"*).

Measuring Displacement in the Static Mode

As a transducer, the bending of the cantilever is measured primarily in one of two ways:

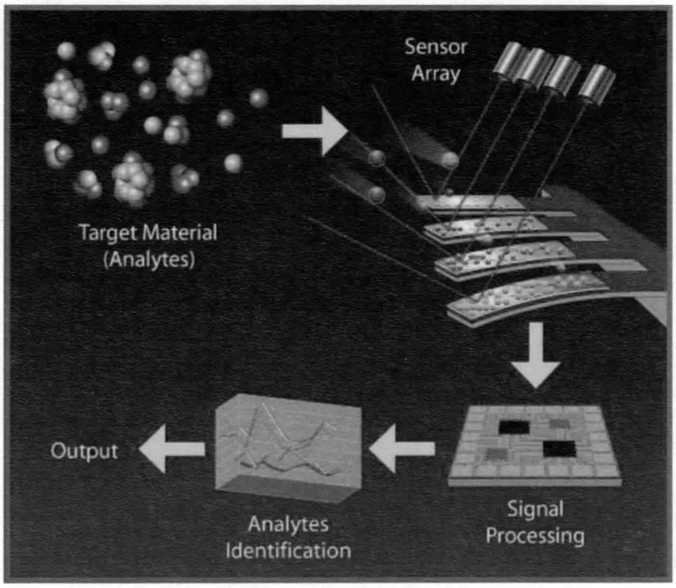


- Change in Angular Deflection (Δ angular deflection) – Reflective material is embedded as a layer onto the surface of the cantilever. A laser beam is directed to and reflected from the cantilever's surface creating a reference angle of deflection (*see figure*). As the cantilever bends the change in the angular deflection is measured. The measuring device is normally a position sensitive light detector.
- Change in resistance (ΔR) - Piezoresistive material is embedded as a structured layer within the cantilever. The piezoresistive layer is normally a doped silicon layer. As the cantilever bends, a change in resistance is measured in the piezoresistive layer. The change in resistance is proportional to the amount of bend (or stress).

The amount of change in resistance and change in angular deflection is a measurement of how much target material is adsorbed.

Application of Static Mode Transducers

A Chemical Sensor Array (CSA) is a MEMS device consisting of an array of microcantilever transducers. Each transducer is coated on one side with a chemically sensitive thin film (probe coating). In a CSA, all of the cantilevers can have the same coating, or single cantilevers or sets of cantilevers can have different coatings. By designing the probe coatings for specific target materials, the array can be customized to detect a variety of different materials within the same sample.



Chemical Sensor Array - Static Mode

As shown in the *Chemical Sensor Array* diagram, specific analytes in the sample are adsorbed by specific probe coatings on the transducers. The surface stress caused by the adsorption of these analytes results in a minute bending of the cantilever. The more analytes adsorbed, the greater the bend. A change in angular deflection is used to measure the amount of bending. This change is recorded by a detector and the signal is processed (*Signal Processing*). The specific types of analytes are identified (*Analytes Identification*). The concentration of each analyte correlates with the amount of change in the angular deflection of its respective laser.

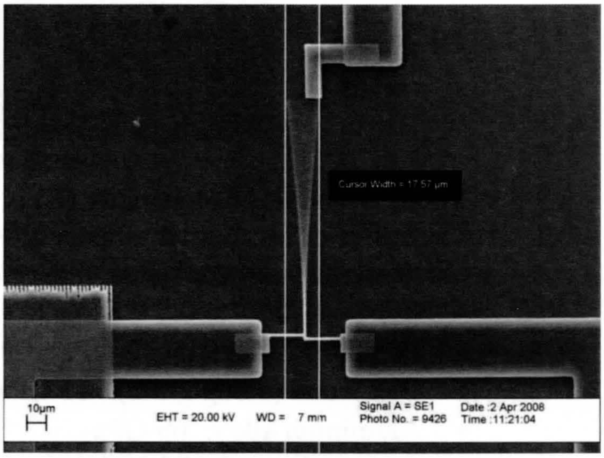
Cantilever Transducers – Dynamic Mode

Chemical sensors also use the dynamic mode of operation to detect and measure specific target materials. Just like the static mode operation, dynamic sensors can consist of one microcantilever transducer or an array of transducers.

In the dynamic mode the amount of target material is measured by monitoring a change in the microcantilever's natural resonant frequency. When a dynamic microcantilever is initially excited by an external actuation such as piezoelectric, magnetic, or electrostatic actuation, it begins to oscillate. The frequency of oscillation is usually at or near the cantilever's natural frequency (or resonant frequency). Any change in the physical characteristics of the cantilever - such as its material, geometry or mass - changes its natural frequency.

Let's Talk about Resonant Frequency

Resonant frequency is the frequency of a system at which it oscillates at maximum amplitude. With little damping, this frequency is usually equal to the system's natural frequency. When a system reaches this resonant frequency, this state is resonance.



MEMS Cantilever in Resonance
This image is a MEMS microcantilever resonating in a Scanning Electron Microscope (SEM)
[Image is licensed under the Creative Commons Attribution – ShareAlike 3.0]

As the mass of the system changes, so does the resonant frequency. For example, when a baby bounces on the end of a diving board the diving board will oscillate at a frequency determined by the diving board characteristics and the mass of the baby. However, if the baby's father and the baby bounce on the end of the diving board, the frequency changes due to a difference in the mass added.

Question: *Which would result in a higher resonant frequency – the baby or the baby and the father?* *(Answer: The baby due to the smaller weight)*

A Bit of Dynamic Theory

$$\omega_0 = \sqrt{\frac{k}{m}} \qquad\qquad k = \frac{Et^3w}{4l^3}$$

Natural Frequency *Spring Constant*

Refer to the equations for *natural frequency* and *spring constant.*

The *natural frequency* (ω_0) of a cantilever is related to its spring constant (k) and mass (m). This is true for both macro and microcantilevers.

For a rectangular cantilever beam, the *spring constant (k)* is a function of
E = Young's modulus of Elasticity (a property of the material)
t = thickness
w = width
l = length

Young's modulus of Elasticity (E) is the measure of the stiffness or elasticity of a given material. The stiffer or less elastic a material is, the higher the E value. Young's modulus allows the behavior of a material to be evaluated under a load or stress. Below are values of E for various materials:

- Rubber: -0.01 to 0.1 GPa
- Polypropylene: 1.5 – 2 GPa
- Oak wood (along grain): 11 GPa
- Aluminum alloy: 69 GPa
- Glass (all types): 72 GPa
- Titanium (Ti): 105 – 120 GPa
- Polycrystalline silicon: 160 GPa
- Tungsten (W): 400 – 410 GPa
- Diamond (C): 1050 – 1200 GPa

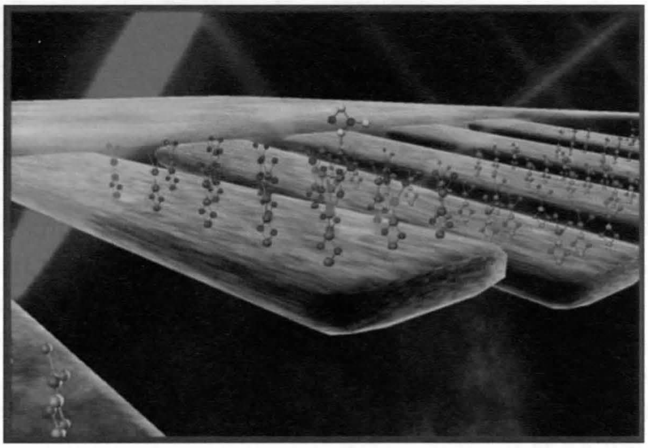
So what do you think?

1. *Which yields the higher frequency – a lower mass or a higher mass cantilever?*
2. *Which yields the higher frequency – a short cantilever or a long cantilever?*
3. *Which yields the higher frequency – a thin cantilever or a thick cantilever?*
4. *Which cantilever material yields a higher frequency – wood or metal, glass or metal? (Assume the same cantilever dimensions)*

5. *What is the spring constant and natural frequency for a poly crystalline silicon cantilever with the following properties:*
    - *2 microns thick*
    - *20 microns wide*
    - *100 microns long*
    - *Polycrystalline silicon density approximately 2.330 kg/cm3*

   (This one requires a little more than just thought. You'll have to do some calculations)

An Application of Dynamic Mode Transducers



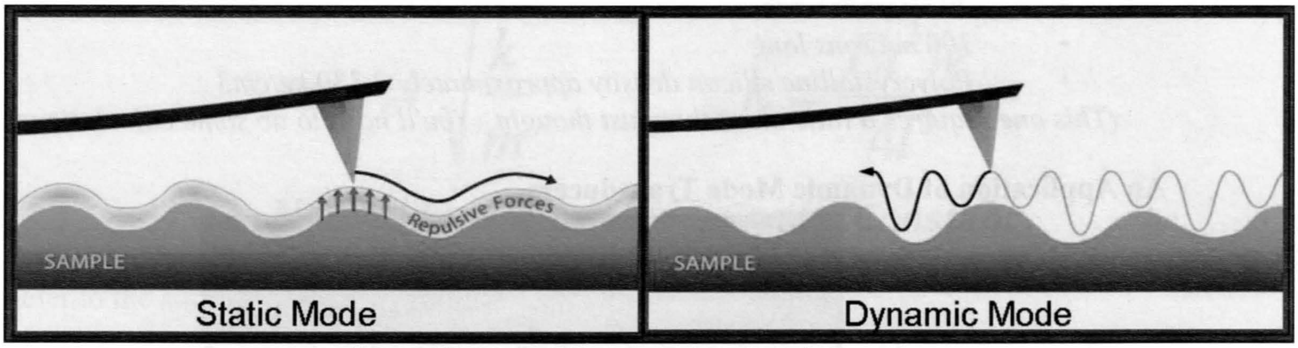
Dynamic Mode Microcantilevers

Dynamic microcantilevers are also used as the transducers for Chemical Sensor Arrays (CSA). In a dynamic CSA, the cantilevers are initially excited by piezoelectric, magnetic, electrostatic or thermal actuation. This input causes the cantilevers to oscillate at their resonant frequencies. When analytes adsorb into the probe coatings on the cantilevers' surfaces it causes a measurable change in the cantilevers' frequencies.

Since the cantilevers are very small (micro-scale), the sensitivity of these transducers is very high. As more and more analytes attach to a surface, the cantilever gains mass on its suspended end. This changes the effective mass of the cantilever. As the mass increases, the resonant frequency of the cantilever decreases. This resonant shift is detected by an appropriate electronic system. The greater the amount of analytes in the sample, the greater the amount of accumulated mass, and the greater the shift in frequency.

[Refer to the SCME Chemical Sensor Array unit for more information on CSAs]

A Little Theory about AFMs



AFM - Static and Dynamic Modes of Operations

Both the static and dynamic modes are used in the Atomic Force Microscope (AFM) *(see figure above)*. In the AFM a cantilever is used to transport a probe or transducer above the surface of a sample. In the static operation (also referred to as the "contact mode"), the probe maintains a path parallel to the sample's surface. In the dynamic operation (also referred to as the "oscillating mode"), the probe oscillates above the sample's surface. The rate of oscillation changes as the z-dimension of the surface changes. *(See SCME's Atomic Force Microscope unit for more information on the AFM.)*

In order for the microcantilever in an AFM to have the sensitivity to map a surface on the nanometer scale, it needs to have a low enough spring constant (k). A low spring constant allows it to respond to very small forces. The cantilever must also have a high resonant frequency so that it does not begin to oscillate on its own, confusing the measurements. If the spring constant is too high or the resonant frequency too low, an AFM's cantilever would not be sensitive enough to the surface variations and would provide noisy data. In addition, this could cause the transducer tip to come in contact with or drag on the sample's surface. This contact could damage the surface, thereby changing the surface being measured.

The spring constant for an AFM microcantilever is about 0.1 N/m. A Slinky has a spring constant of 1.0 N/m, ten times that of a microcantilever. The higher the spring constant (k), the higher the resonant frequency (ω_0) for the same mass (m).

An AFM cantilever has a very small mass (as low as 10^{-10} g). Therefore, with a low mass, an AFM cantilever can still have a high resonant frequency, even though its spring constant is low in comparison. *(Refer to the previous equations under "A Bit of Dynamic Theory.")*

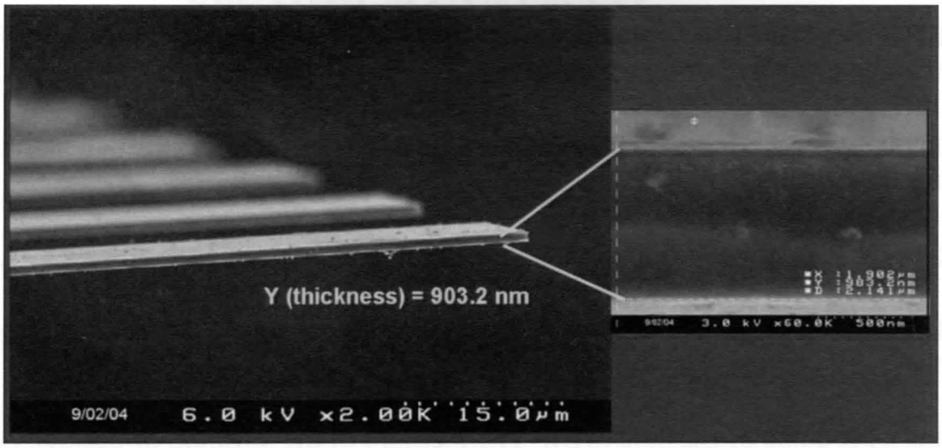
Review Questions

How are macroscopic cantilevers similar to microscopic cantilevers in their operation?

How are they different?

What causes a microcantilever to *bend*?

Summary



Microcantilevers in an array
[Image courtesy of Lawrence Livermore National Laboratories]

Microcantilevers are used for a wide variety of MEMS applications. The specific application determines the dimensions of the cantilever and its materials.

The microcantilever is the cornerstone component of microsystems. It is used in a wide variety of applications including micro-chemical sensor arrays, atomic force microscopes, microswitches, needles and probes.

As transducers microcantilevers are operated in the static and the dynamic modes.

Glossary of Key Terms

Angular deflection: The angle formed between the two extremes of deflection.

Atomic Force Microscope: A device for mapping surface atomic structures by measuring the force acting on the tip of a sharply pointed object that is moved over the surface.

Cantilever: A beam supported at one end and with the other end suspended freely outwards.

Chemical sensor array: An array of sensors that chemical reacts with a target material resulting in a measurable change (i.e. resonant frequency or mass) with the sensor.

Displacement: The difference between the initial position of something (as a body or geometric figure) and any later position.

Dynamic: Of or relating to energy or to objects in motion.

MEMS: Micro-Electro Mechanical Systems – microscopic devices such as sensors and actuators, normally fabricated on silicon wafers.

Piezoresistive: The piezoresistive effect describes the changing electrical resistance of a material due to applied mechanical stress.

Resonant frequency: The frequency at which a moving member or a circuit has a maximum output for a given input.

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

Spring constant: For an object that obeys Hooke's law, spring constant is the force per unit extension (N/m).

Static: Of or relating to bodies at rest or forces that balance each other.

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

Young's Modulus of Elasticity (E): The measure of the stiffness or elasticity of a given material. The stiffer or less elastic a material is, the higher the E value.

Related SCME Units

- MEMS Cantilever Applications
- Cantilever Activity: Resonant Frequency vs. Mass
- Cantilever Inquiry Activity II: Static Movement
- Chemical Sensor Arrays
- Atomic Force Microscopes

References

1. "Cornell researchers move beyond 'nano' to 'atto' to build a scale sensitive enough to weigh a virus". Bill Steele. Cornell News. April 2, 2004.
2. "Cantilever In-Class Activity (PowerPoint Presentation)". Mathias Pleil. Southwest Center for Microsystems Education (SCME). University of New Mexico.
3. "Cantilever In Electromechanical Systems" – Wikipedia. http://en.wikipedia.org/wiki/Cantilever

Disclaimer

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

<u>MEMS Applications Topic</u>

Chemical Sensor Arrays

Primary Knowledge (PK)
Shareable Content Object (SCO)

This SCO is part of the Learning Module
<u>MEMS Cantilevers</u>

Target audiences: High School, Community College.

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Chemical Sensor Arrays
Primary Knowledge

MEMS Cantilever Learning Module
Participant Guide

Description and Estimated Time to Complete

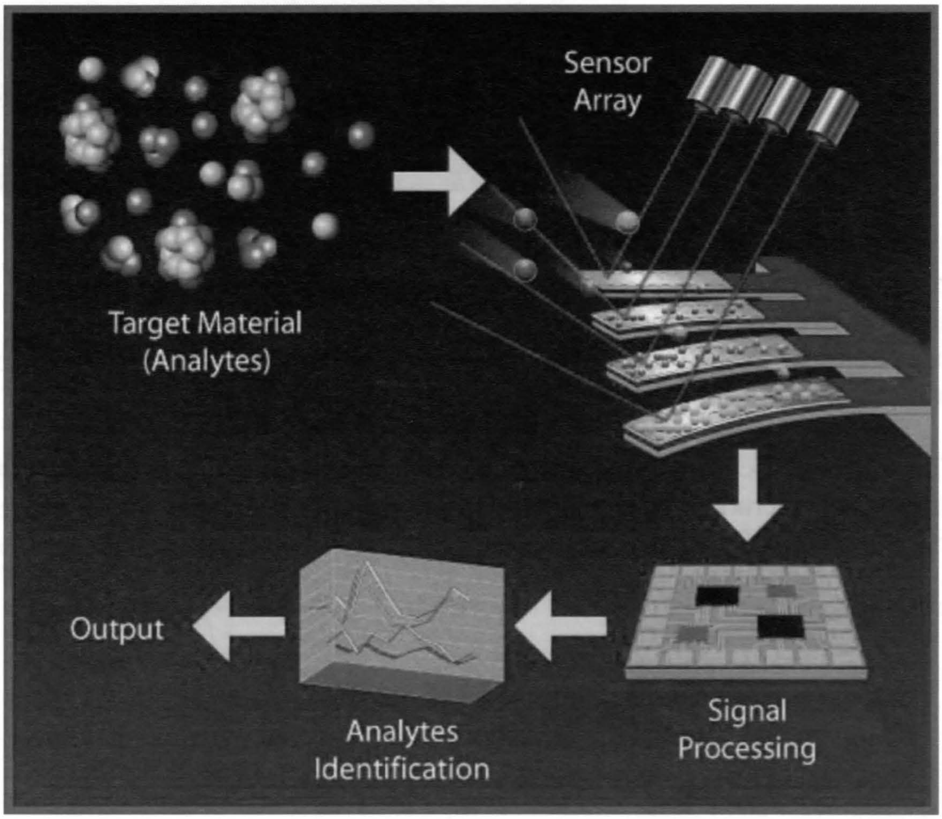
Chemical Sensor Arrays (CSA) are MEMS devices that gather, detect, measure, and identify a substance or several substances in a minute sample. That sample could be a few drops of blood, an unknown gas or smell, or an unknown liquid. Many of these arrays are cantilever-based, using micro and nano-sized cantilevers. This unit provides information about MEMS Chemical Sensor Arrays, primarily the cantilever-based arrays. It covers how they work and where they are used.

It would be to your benefit to have reviewed SCME's "How Does a Cantilever Work?" prior to completing this unit.

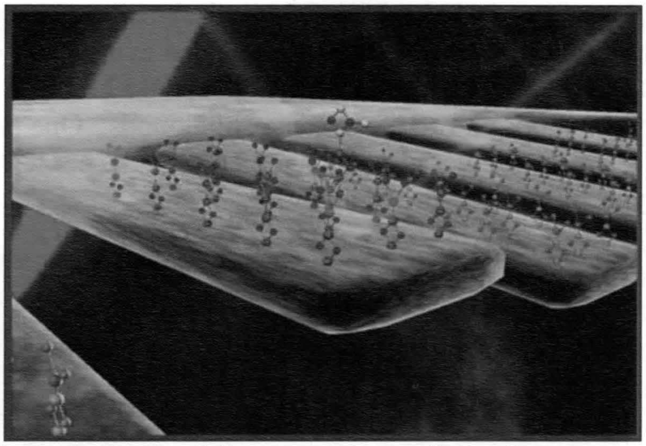
<u>Estimated Time to Complete</u>
Allow approximately 20 minutes

Introduction

A Chemical Sensor Array (CSA) is an array of microtransducers and supporting integrated circuits *(see process flow diagram below)*. A CSA is designed to detect and measure the amount or concentration of one or more substances contained in a sample environment. The substances, referred to as target materials or analytes, could be specific gas molecules or atoms, antibodies or proteins, mercury vapor or volatile organic compounds. One or more analytes in a sample are detected and the quantity measured using microtransducers. The system electronics analyze and identify the type and/or quantity of analytes.



The microtransducers of CSAs could be optical devices, electronic diodes, microcantilevers, biological cells and molecules (biological, physical or chemical). The application and, more specifically, the target material being analyzed, determine the type of transducer used. The most common transducer used in CSAs is the microcantilever.



Chemical Sensor Array with Analytes

In a cantilever-based CSA, the target material is detected when it comes in contact with a chemically sensitive material on a cantilever's surface *(see figure above)*. The amount of target material is measured by monitoring a change in one or more of the cantilever's mechanical or electrical properties, such as displacement, resistance, or resonant frequency.

This unit will focus on the applications of chemical sensor arrays and the operation of cantilever-based CSA operation. Many of the following applications are not cantilever-based, but rather an array of electrodes, diodes, or biomolecules use to detect specific molecules.

Objectives

- State at least five applications of a MEMS CSA.
- Compare and contrast the operations of a static and dynamic cantilever-based CSA.
- Describe at least two operating characteristics of a CSA.

Chemical Sensor Array Applications

The MEMS Chemical Sensor Array (CSA) is an analytical tool used in a variety of applications and microenvironments. It is currently used to monitor glucose levels in diabetics, detect fuel leaks in a space shuttle, identify toxic gases in an environment, identify various types of cells in a blood sample, and analyze DNA hybridization. Common applications of MEMS CSAs are found in the following fields:

- Medical
- Forensics
- Environmental control
- Aerospace
- Fragrance design
- Food production
- Security and defense

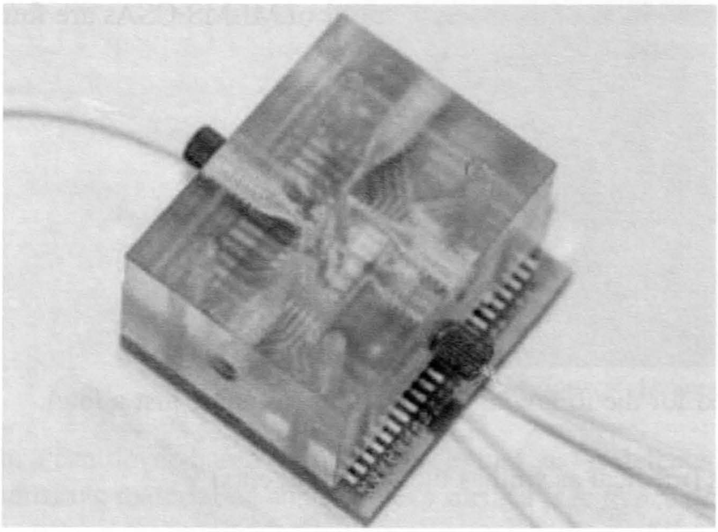
Within these fields, CSAs are used for the following applications (to name just a few):

- Detection of chemical vapors
- Detection of biological agents (medical as well as biowarfare agents)
- Vibration monitors
- Medical diagnostics and therapeutics
- Olfactory applications
- Sample analysis (gas or liquids)

Following are briefs descriptions of some chemical arrays that are already on the market or currently being tested for the market.

Lab-on-a-Chip (LOC) Array

A lab-on-a-chip (LOC) is a MEMS that incorporates several laboratory functions on a single chip. An LOC can consist of a chemical sensor array designed to sense one or more analytes, a micropump to handle the flow of the sample to and from the array, and the electronics to control the device and analyze the output of the CSA.

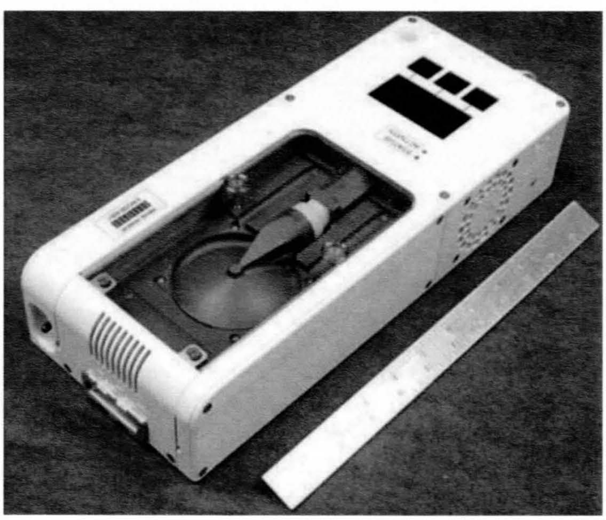


This Lab-on-a-chip (LOC) is a miniaturized, portable version of a blood-count machine that is being tested by astronauts. One portion of the LOC uses a CSA to analyze blood samples in real-time to diagnose infection, allergies, anemia or deficiencies in the immune system.[1]

Lab-on-a-chip – Blood Analysis Chemical Sensor Array
[Photo courtesy of Y. Tai, California Institute of Technology]

The Artificial Nose (or ENose)

For fragrance design, food production, and gas detection, the CSA is used as an artificial olfactory system (an artificial nose). It analyzes a fragrance by separating the component particles that when combined, provide an overall scent. In food production, MEMS CSAs are used to detect specific compounds in a food's odor, such as the odor of a fish or meat. By analyzing the amount of the compounds present, a CSA can determine the freshness of the meat or the presence of contaminants.[2]



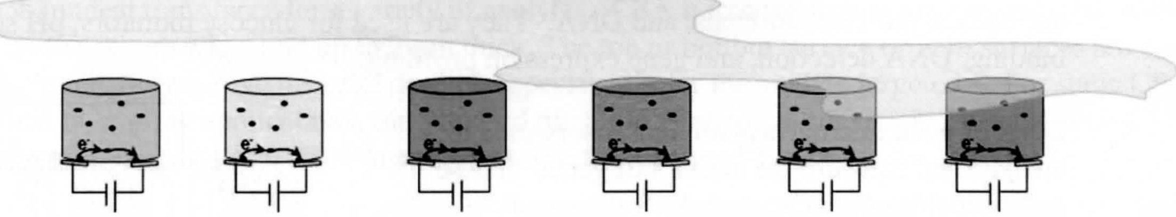
The picture is the ENose developed by NASA and tested on the International Space Station in late 2008. The ENose Sensor Unit (the darker-looking metal object) is housed in its Interface Unit (white). The ruler, shown for size comparison, is 12 inches (about 30.5 cm) long.[3]

The ENose developed by NASA's Advanced Environmental Monitoring and Control division [Graphic source: NASA]

For gas detection, the artificial nose can detect a specific gas or the composition of a gas. The artificial nose is currently used in the space station to detect ammonia.[3] In counterterrorism CSAs are being designed to detect toxic and hazardous gases in the field. Such devices could be incorporated into the helmets or clothing of military personnel.

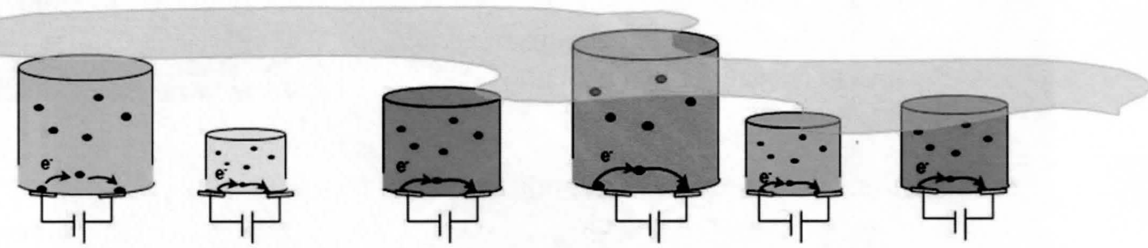
How Does the ENose Work?[4]

(a)



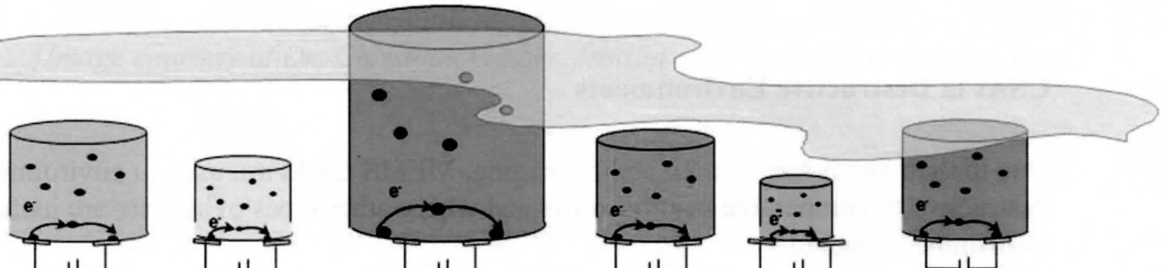
The ENose uses a collection of 16 different polymer films on a set of electrodes. The graphic (a) illustrates six films/electrodes. These films are specially designed to conduct electricity based on their resistance. A baseline resistance reading is established (a) with no odors (ambient air). When a substance -- such as the stray molecules from an ammonia leak -- is absorbed into these films, the films expand slightly (b), changing their resistivity. The amount of expansion of each film determines the amount of its electrode current.

(b)



Because each film is made of a different polymer, each one reacts to a chemical compound in a slightly different way. While the changes in resistivity in a single polymer film would not be enough to identify a compound, the varied changes in 16 films produce a distinctive, identifiable pattern for a specific compound. Graphic (c) shows a different compound being sensed.

(c)



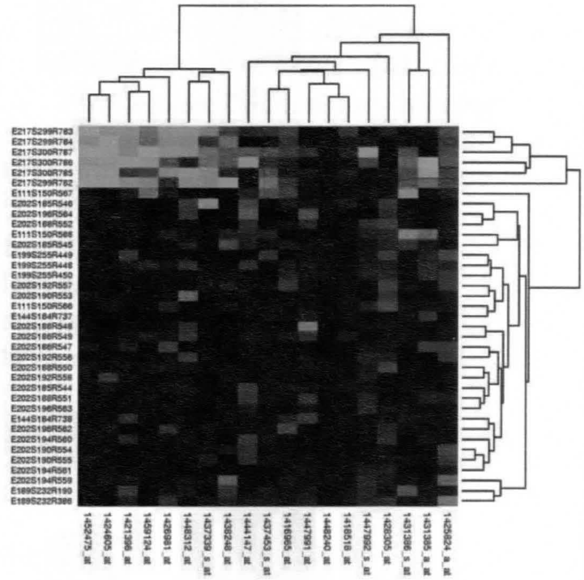
[Graphics Courtesy of NASA's Advanced Environmental Monitoring and Control division]

Bio-Sensors

In medical diagnostics, CSAs are used as bio-sensors to analyze samples for substances such as antibodies, proteins, antigens, and DNA. They are used for glucose monitors, pH sensors, protein binding, DNA detection, and gene expression profiling.

DNA or gene microarrays are biosensors used to analyze and measure the activity of genes. These arrays enables scientists and doctors to analyze complex biological problems:

- Identify the genetic variations that could play a role in diseases such as Alzheimer's and Parkinson's.
- Analyze and test for viruses that cause diseases such as SARS (Severe Acute Respiratory Syndrome), HIV, tuberculosis, and other infectious diseases.
- Analyze a patient's blood to determine the best drug and dosage for that patient's particular disease.



Gene expression values from microarray experiments can be represented as heat maps to visualize the results of data analysis. The green represents reduced gene expression or activity. [Image is public domain. Image source: Wikipedia: Gene Expression Profiling]

Researchers can use microarrays and other methods to measure changes in gene expression (activity) and thereby learn how cells respond to a disease or to some other challenge.[5] Gene expression microarrays *(image right)* measure tens of thousands of genes on a single GeneChip™ and provide scientists the data to understand regulatory processes at the cellular level.

CSAs in Destructive Environments

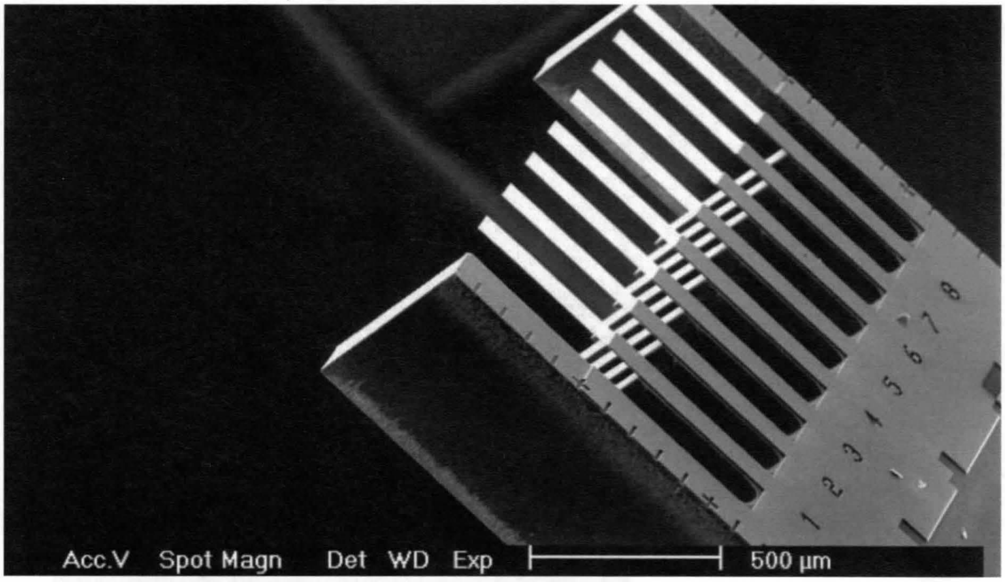
Due to their small size, design and packaging, MEMS CSAs are used in environments that are destructive to comparable macrosensors and where other types of sensors are ineffective. Such environments include

- electric and magnetic fields,
- hazardous chemical vapors,
- nuclear radiation,
- radio frequency (RF) radiation, and
- contaminated and hazardous liquids.

The Cantilever-based CSA

The most common CSA transducer is the microcantilever. Its versatility and low construction costs make it an ideal transducer for a variety of analytes. CSA microcantilevers are typically 10 – 500 µm long, up to 100 µm wide, and up to 2 µm thick. The top or bottom surface or both surfaces are coated with a chemically reactive material designed specifically for the analyte targeted. [2] For static CSA's in optical fiber array applications, the standard pitch of the microcantilevers is 250 mm, with a typical spring constant of 0.02 N/m and resonance frequency of 4 kHz. [2]

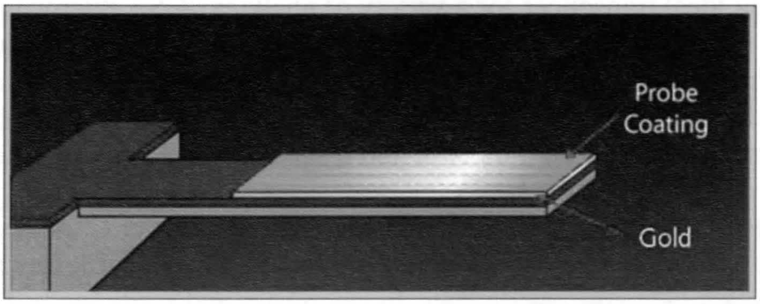
The scanning electron image below is of a microcantilever CSA developed by the Cantilever Array Sensor Group at the Swiss Nanoscience Institute. Such cantilevers are being developed for "applications in chemistry, physics, biochemistry and medicine". They are ideal for such applications because they "are miniaturized, ultrasensitive and fast-responding sensors."[13]



Microcantilever Chemical Sensor Array
[Image courtesy of Dr. Christoph Gerber, Institute of Physics, University of Basel]

How does a Cantilever-Based CSA work?

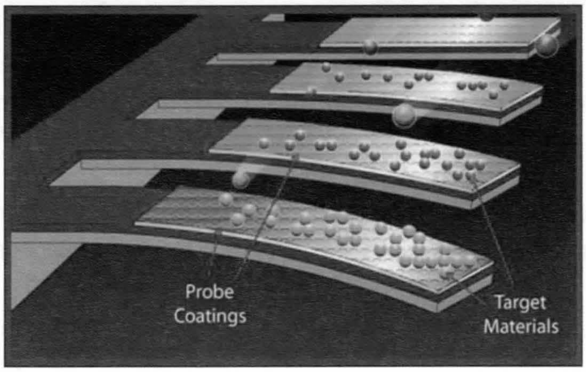
Cantilever Construction



Chemically Reactive Probe Coating

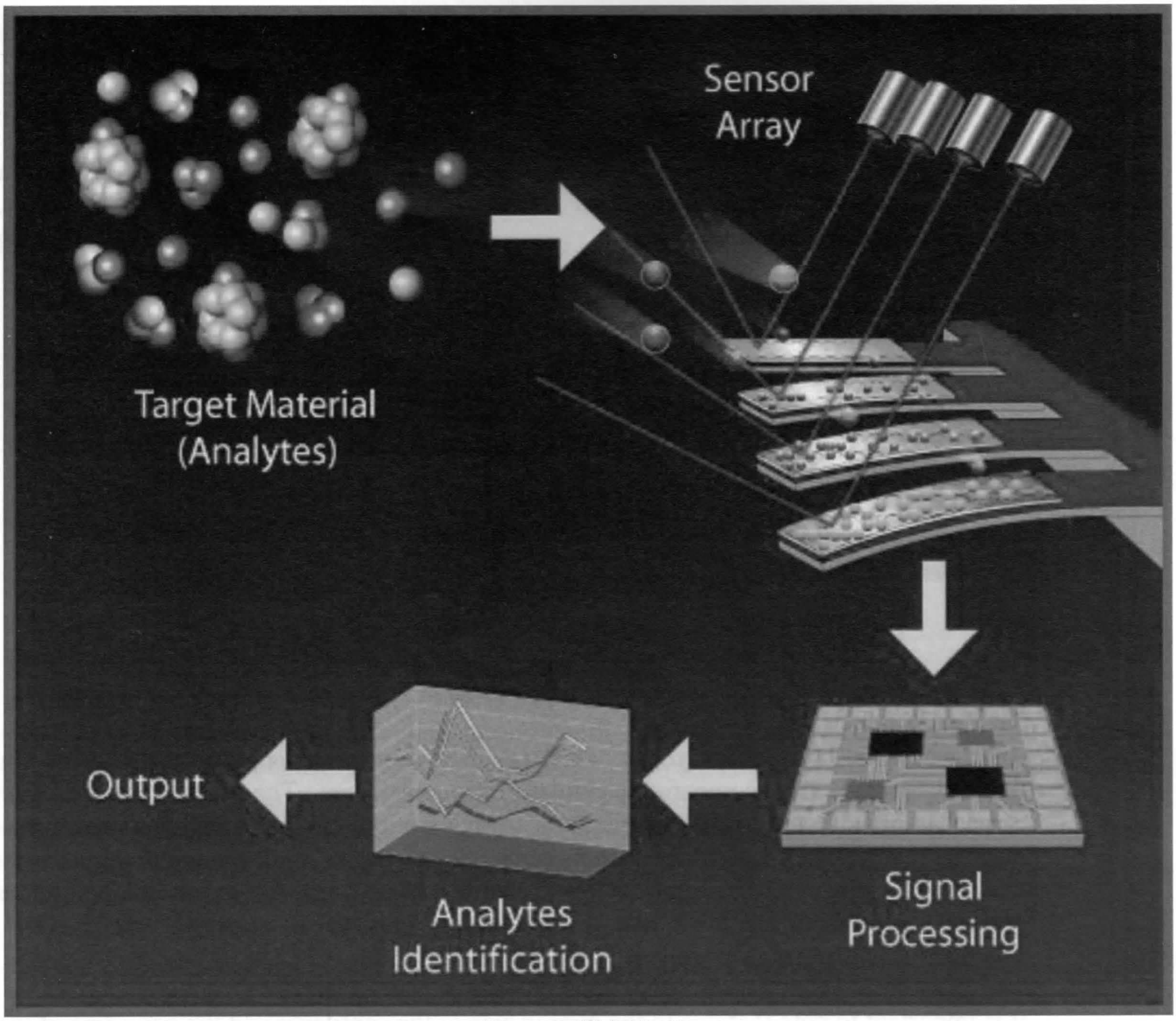
The primary components of a CSA are the microcantilever transducers. The suspended end of each microcantilever is coated with a probe material that has an attraction to specific molecules in the test environment. For cantilever-based CSAs, the cantilevers can be constructed with different surface materials on the top and the bottom. In some CSAs, the top surface is coated with a chemically reactive coating (probe coating) which may exist at the suspended end of the cantilever or may cover the entire top surface. In the fabrication process, the deposition of this selective coating is referred to as "functionalizing the surface." By functionalizing the surface, the cantilever can be designed to have the target material "stick to" or adsorbed to a specific portion of the cantilever's surface (e.g. the tip, the middle, the full length of the cantilever or both the top and bottom surfaces). The fabrication process can be designed to selectively coat only the desired portion of the cantilever's surface with the chemically reactive coating.

On the bottom of the cantilever, the coating may be to be neutral so that it will not react with any of the substances in the sample environment. However, some applications have the probe coating on both the top and bottom surfaces of the cantilever.



Probe Coating and Analytes (Target Material)

The probe material is a chemically sensitive substance that experiences a chemical change when it adsorbs a specific target material (analyte). By designing a CSA with a different probe coating on each cantilever, a CSA can be used to detect several different substances within the same sample. The figure *(Probe Coating and Analytes)* illustrates an array that can detect three different analytes (green, purple and red). The fourth microcantilever is the reference cantilever.



How a CSA Works

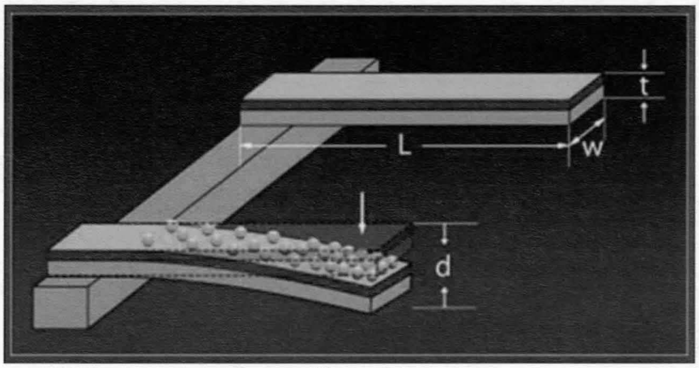
(Refer to figure: "How a CSA works") When a target material in the sample binds to the probe coating on a cantilever's surface, it causes a minute, but measurable change in the cantilever's mechanical or electrical properties. As more target material attaches to the cantilever's surface, the resulting change is measured. This change is processed by the integrated circuitry (Signal Processing) of the MEMS into relative data. This data is analyzed and compared to reference data for determining the type and amount of material (Analytes Identification).

One or more of the cantilever's properties are monitored. The properties monitored depend on the design of the system. Some systems monitor a static property such as displacement or resistance. Others monitor a dynamic property such as resonant frequency. (Note about resonant frequency: Mechanical systems *like* to vibrate at a natural frequency which is a property of their geometric design. The natural frequency is at or near the system's resonant frequency.)

An Interesting Fact

It is interesting to note, that prior to the onset of micron and nano-technology, these minute changes in the mechanical properties of such small devices were considered negligible. However, current technology provides innovative methods for measuring these negligible changes allowing microscale components to be monitored and measured like their macroscopic equivalents.

Mass-Sensitive Transducer

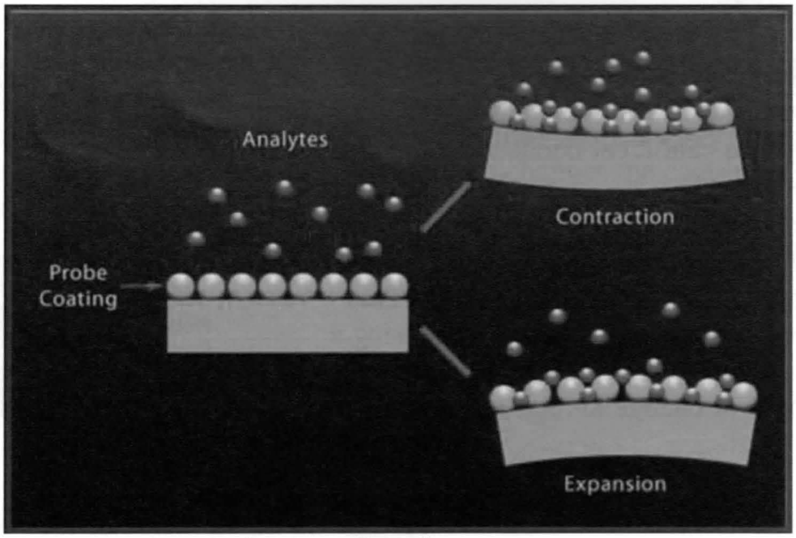


Microtransducer affected by change in mass

Since cantilever transducers are very small (from a few nanometers to hundreds of microns in size), their sensitivity is high compared to similar macrotransducers. The overall mass of a microcantilever is measurably affected by the chemisorption or adsorption of a very small quantity or mass of material (even a few molecules or atoms can be detected). A small change in mass causes a measurable change in one or more of these cantilever's properties. For example, more mass causes a greater displacement or a lower resonant frequency. This type of cantilever transducer is referred to as a mass-sensitive transducer.

It is important to note that due to the micron size of the cantilever and the nano size of the analyte, the cantilever's *bend or displacement* is due to a small amount of mass, not weight. Weight is mass affected by the force of gravity. A diving board is a cantilever that *bends* due to the weight of a person standing on its suspended end. The microcantilever has too little mass to be affected by the force of gravity.

Stress-Induced Curvature



Stress-induced curvature

Mass-sensitive transducers are not as effective as the transducer and analytes get smaller. For applications such as biomedical diagnostics and gas detection, the analytes can be nano-sized particles (1 to 100 nm). For such applications, cantilever displacement is dependent upon a surface stress caused by the chemisorption of the analytes on or within the probe coating. When the analytes adsorb into the probe coating an expansion or contraction occurs *(see figure)*. This cause the cantilever to bend or flex. This is called "stress-induced curvature."

Static and Dynamic CSAs

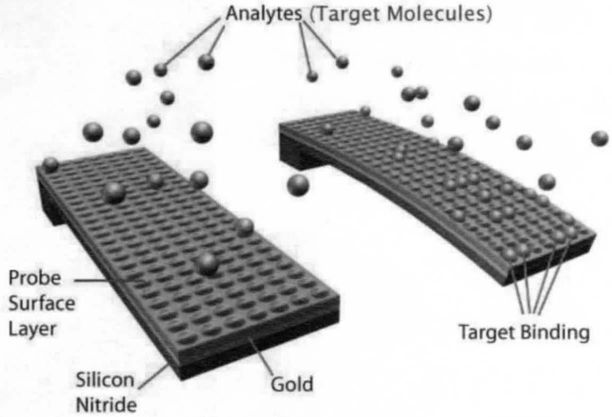
There are two operational modes used to detect changes in the cantilever's mechanical or electrical properties: **Static and Dynamic**.

The **static mode** measures the bending or flexing of the cantilever due to stress or a change in mass. When the probe coating captures the target analytes, the cantilever bends due to an increase in mass or stress of the probe coating. This bending is a measurable static response.

The **dynamic mode** measures a shift in the cantilever's resonant frequency due to an increase in mass. When the probe coating captures the target analytes, the cantilever's resonant frequency shifts to a lower frequency. This shift is due to an increase in mass which is seen as an increase in the cantilever's overall mass.

Static Mode

In the static mode of operation, as the chemically reactive surface selectively adsorbs the target material, the cantilever bends due to an increase in mass or surface stress caused by an increase of analytes bonding to the probe coating's molecules *(see figure)*. The bending causes a measurable cantilever displacement. This displacement can be measured by sensing a change in angular deflection (Δ angular deflection) or change in resistance (ΔR).



Cantilever displacement due to surface stress

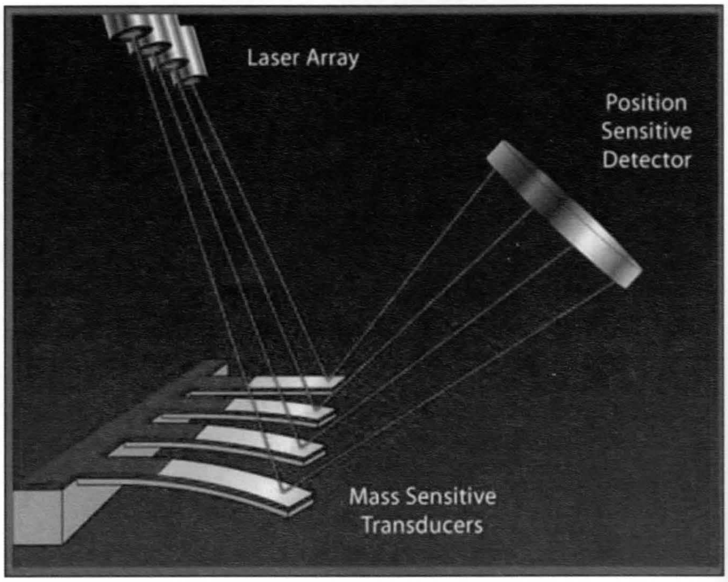
Static - ΔR

To measure a change in resistance, the microcantilevers are constructed with a piezoresistive layer. This layer is usually a doped silicon layer fabricated into the cantilever during construction. As the target material is adsorbed by the chemically reactive layer the cantilever bends. This creates a measurable change in the resistance of the cantilever's piezoresistive layer.

Static – Δ angular deflection

To measure a change in angular deflection, a reflective layer consisting of a material such as gold is coated onto the surface of the cantilever prior to the chemically reactive layer. A laser beam is directed to and reflected from the cantilever's surface creating a reference angle. As the cantilever bends, the change in the angular deflection is detected by measuring the change in position of the reflected beam.

With both measurements, the amount of change in resistance or change in angular deflection is related to the amount of target material adsorbed in the probe coating.

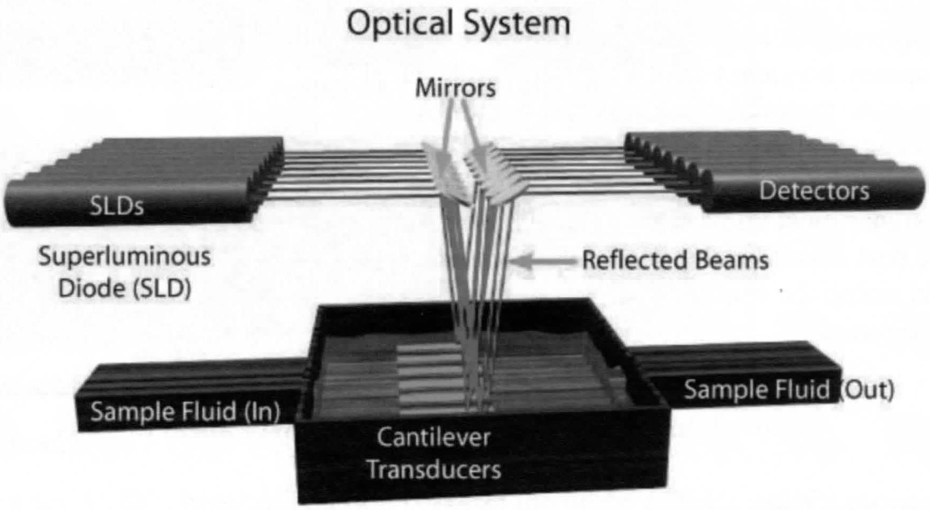


Measuring Displacement with a change in Angular Deflection

Dynamic Mode

In the dynamic CSA, the cantilevers are initially excited by a piezoelectric, magnetic, electrostatic or thermal actuation. Target molecules in the sample environment attach to each of the cantilevers' surfaces. As with the static mode, the selective probe material on the cantilevers' surfaces determines which molecules adsorb to which surface. This adsorption changes the cantilever's mass resulting in a change in resonant frequency. The amount of change in resonant frequency is a function of the amount of mass loading. The change in mass is dependent upon the concentration of the target material within the sample environment and the amount of time the cantilever is exposed to the sample.

Static or Dynamic?



CSA for Liquid Environment

The type of CSA (static or dynamic) used for a specific application is determined by the sample environment. In liquid environments the damping effect of the liquid on the cantilever's movement can make frequency measurements very difficult resulting in false readings. Therefore, static CSA's are primarily used in liquid environments *(see figure above)*. In gaseous environments, both static and dynamic CSA's are used. In order to gather more information from the sample and ensure its accuracy, some CSAs use a combination of static and dynamic modes.

Operating Characteristics of CSAs

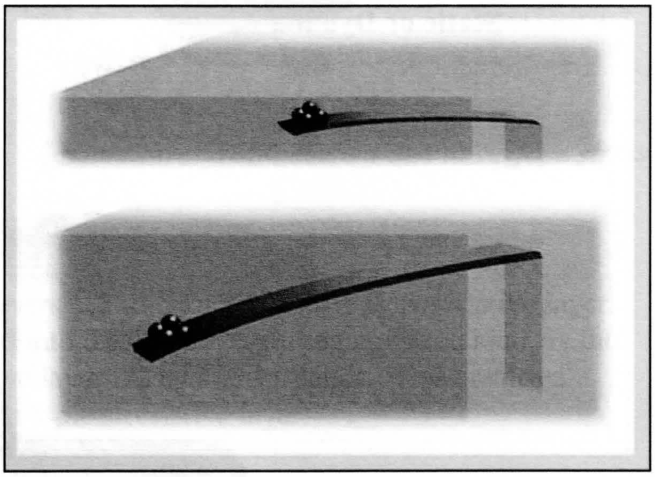
A few of the operating characteristics considered in the design of CSA microcantilevers include

- sensitivity,
- selectivity,
- response time,
- size, and
- power consumption.

Cantilever-based CSAs have proven to be highly sensitive, highly selective, and to have fast response times. Because each cantilever in an array can be coated with a different probe material, a single cantilever array can be designed to detect a large number of different analytes. It can also be designed to have redundancy (nominally identical sensors) in order to reduce false positives (greater accuracy) and yield a better response. Such an array can analyze a broad spectrum of materials within a single complex mixture. For example, rather than have to take several vials of bloods to test for different analytes using various test processes, technicians could place a drop of blood on a CSA and it could test for all of the different analytes simultaneously.

Mass Sensitivity

Cantilever transducers have an inherently high mass sensitivity due to the small mass of the cantilever itself. The physical properties of the cantilever (width, thickness, length and material) are used to further enhance its sensitivity to minute changes in mass. For example, the physical geometry of the cantilever affects its resonant frequency. A long cantilever will have a lower resonant frequency than a shorter cantilever of the same material, thickness and width. A thicker cantilever is inherently stiffer, yielding a higher frequency. Therefore, the CSA designer must know what detection electronics are best suited for the operational frequencies and match the cantilever design to the electronics.



Cantilever length - short vs. long

Response Time

The response time for a microcantilever is the time it takes for the cantilever to respond to the target material on its surface and produce a change in the output. The response time is affected by several parameters, three of which are

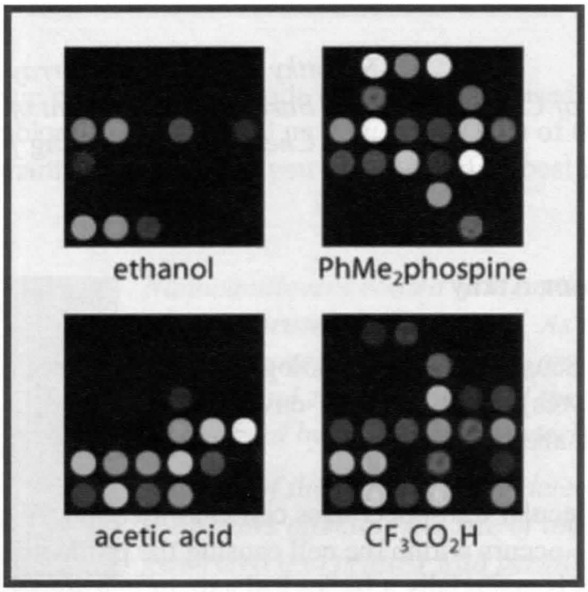
- the concentration of the target material in the environment,
- the probe material itself, and
- the method used to interpret the change in a mechanical property.

For the best response time, the chemical reaction between the target material and the probe material must be as fast as possible. The more time it takes for the adsorption to occur, the slower the response time. Once the chemical reaction occurs, the change it creates in the frequency, resistance or deflection must be sensed quickly in order to generate an immediate output. In a CSA this change is measured by integrated circuits directly interfaced with the monitored characteristic of the cantilever (i.e. the piezoresistance, resonant frequency, or angular deflection). This direct measurement coupled with the time required for the chemical reaction to occur on the cantilever's surface determine the sensor's response time.

Non-Cantilever Based CSAs

The type of CSA discussed in this unit is a cantilever-based CSA that uses mass or stress sensitive transducers. There are variations of CSAs that use other types of transducers that may be better suited for a specific application and its requirements. Following is a short description of other types of non-cantilever based CSAs.

Optical Sensor Array



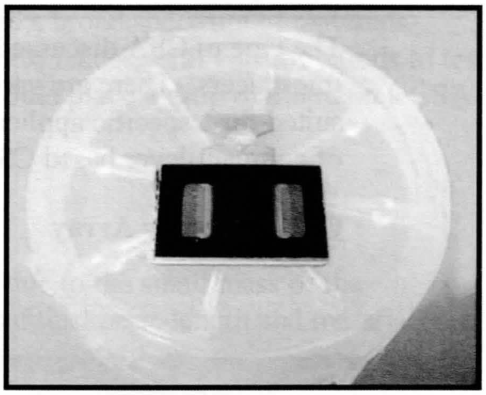
Partial output from a Colorimetric Optical Array.

In optical sensor arrays the chemical reaction between the probe coating and the target analytes affects an optical property of the transducer. This results in a change in the optical signal such as color (wavelength) or light intensity.

The graphic shows a partial output from a colorimetric optical array. A colorimetric sensor arrays act as an "optoelectronic nose" by using an array of multiple dyes whose color changes are based on the full range of intermolecular interactions. The four volatile organic compounds in the graphic have four different patterns as identified by the sensor array. This particular array can sense up to 15 analytes simultaneously in the same sample.

Schottky Diode Array

In a Schottky Diode Sensor Array the target material absorbs (diffuses) through the probe coating to a metal layer. The metal layer serves as a gate for a diode. Any change at the gate causes a change in the diode's electrical characteristics.



Schottky Diode Sensor Array [University of California, Santa Barbara, Department of Chemical Engineering.]

Cell-based Sensor Array

The Cell-based Sensor Array uses biological cells as the transducers to detect the presence of specific molecules (analytes) within the cells' environment. There are several types of molecular transducers being developed and tested.

One type of molecular transducer uses cell amplification. When a cell interacts with the analytes a chemical change occurs within the cell causing the production of many "so-called second messenger" molecules. This is essentially a biological gain or cell signal amplification. A chemical change within the cell or an electrical activity can be monitored to measure the amount of amplification. The amount of amplification indicates the amount of analytes in the sample.[6]

CSAs Working Together

With the variety of sensor arrays available, a system can be developed to mimic the human senses. Cantilever-based arrays distinguish between different smells and tastes, optical arrays react to different wavelengths and intensities (sight), and acoustic arrays detect a change in acoustic properties as a result of interacting with the environment (hearing).

A CSA can be used in combination with other sensors or as a stand-alone device. Its versatility, reliability, selectivity and design flexibility make it an ideal sensor system for a variety of applications, many of which are still being realized.

Summary

A Chemical Sensor Array is an array of microtransducers and supporting integrated circuits. A CSA is designed to detect and measure the amount or concentration of one or more substances contained in a sample environment.

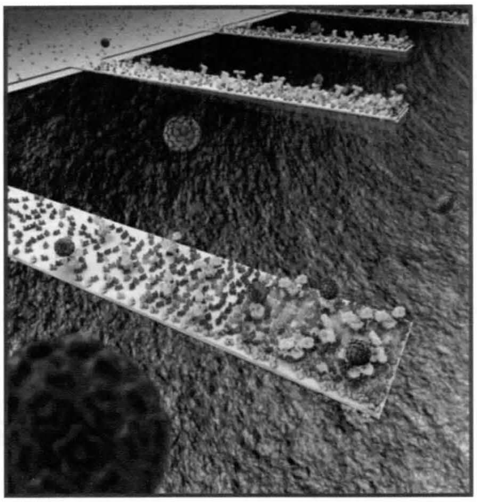
The cantilever-based CSA uses an array of microcantilevers to detect and measure specific materials within a sample environment. The micron size of the cantilevers results in higher selectivity, improved sensitivity, faster response time and low construction costs. These characteristics make the cantilever CSA a very popular sensor for a wide range of applications.

Food For Thought

What are some additional applications where CSA's could be used to detect a combination of gases, scents or particles?

In the dynamic mode, which microcantilever would be more sensitive to mass loading – one 100 microns in length or 60 microns in length? (Assume the thickness, width and materials are the same for both cantilevers).

In many applications, dynamic mode or static mode CSAs could be used. Below is a CSA used to detect a specific virus in the bloodstream. Based on your knowledge of the microcantilever modes of operation, which mode – dynamic or static – do you think would be best for this application and why?



Nanocantilevers coated with antibodies (blue-green) that capture viruses (red spheres). As the cantilevers identify and capture more virus molecules, one or more of the mechanical or electrical characteristics of the cantilevers can change and be detected by an electronic interface.*

The size of the particle being detected and captured is one of the factors affecting the size of the cantilever. [Image generated and printed with permission by Seyet, LLC]

**Antibodies are proteins produced in the blood in response to the presence of an antigen (e.g., virus, bacteria, toxin).*

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Glossary

Analytes: A substance or chemical constituent that is undergoing analysis or being measured.

Cantilever: A beam supported at one end and with the other end suspended freely outwards.

Chemical Sensor Array: An array of sensors that chemical reacts with a target material resulting in a measurable change (i.e. resonant frequency or mass) with the sensor.

Chemisorption: The molecular bonding of gas to a solid.

MEMS: Micro-Electro Mechanical Systems – microscopic devices such as sensors and actuators, normally fabricated on silicon wafers.

Piezoresistive: The piezoresistive effect describes the changing electrical resistance of a material due to applied mechanical stress.

Resonant frequency: The frequency at which a moving member or a circuit has a maximum output for a given input.

Selectivity: The pumping speeds for specific gases. Pumps that are selective do not pump all gases at the same rate.

Related SCME Units

- MEMS Cantilever Applications Overview
- How Does a Cantilever Work?
- MEMS Cantilever Inquiry Activities I and II
- MEMS Cantilever Activity: Resonant Frequency vs. Mass

Disclaimer

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