# Microcantilever Applications Overview

## Primary Knowledge
## Instructor Guide

**Notes to Instructor**

Microcantilever Applications Overview is the introductory primary knowledge unit for the Microcantilevers Learning Module.

The Microcantilevers Learning Module consists of the following:

- *Book 1*
- Learning Module Map for Instructors
- Microcantilever Knowledge Probe
- **Microcantilever Applications Overview (PK)**
- Chemical Sensor Arrays (PK)
- Atomic Force Microscopes (PK)
- *Book 2*
- How Does a Cantilever Work? (PK)
- Microcantilever Model Activity:  Resonant Frequency vs. Mass (SCME Kit Available)
- Microcantilevers Terminology and Research Activity
- Final Assessment

**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


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, microcantilevers can be as thin as a few nanometers with lengths that range from a few microns to several hundred microns. Microcantilevers are used in a variety of microelectromechanical systems (MEMS) as micro transducers, sensors, switches, actuators, resonators, and probes.

This unit discusses some of the more common applications of microcantilevers. 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 microcantilevers are used.
- Discuss the advantages and limitations of microcantilevers compared to larger cantilevers.

**Microcantilever Applications**

Microcantilevers, also called 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 microcantilever 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) [Courtesy of Lawrence Livermore National Labs]*

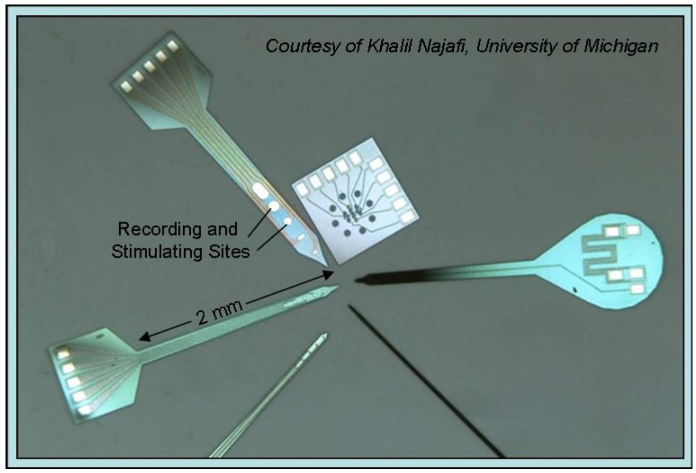
**Microcantilever Fabrication**

Microcantilevers 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 below)* 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.

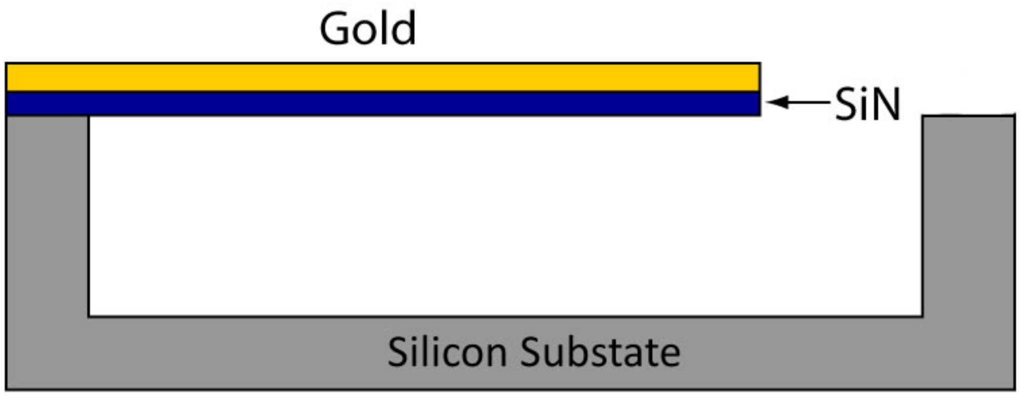
However, such devices may need certain electrical characteristics not required by biomedical needles. Some cantilever sensors and transducers are fabricated with materials that expand or contract due to chemical reactions or particle interactions.

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.




*Probes with MEMS sensors at the probe tips*

**Microcantilevers Fabrication Methods**




*Cantilever Beam released from Silicon (Bulk micromachining)*

Microcantilevers 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.

**Microcantilever Characteristics**

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

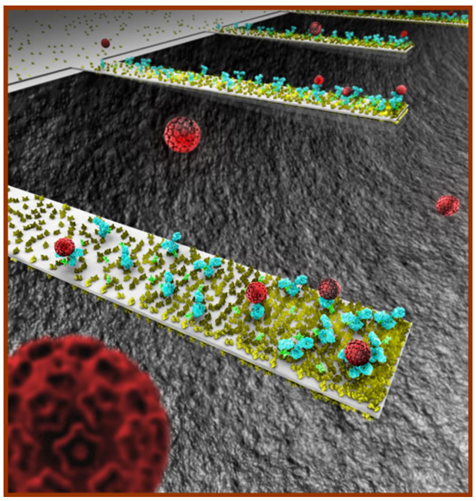
- Ability to render measurable mechanical responses quickly and directly
- Sensitivity to a miniscule amount of external force or stimuli
- Low power consumption
- Capability to fabricate a high density array with simultaneous responses to different stimuli

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

**Microcantilevers 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).*

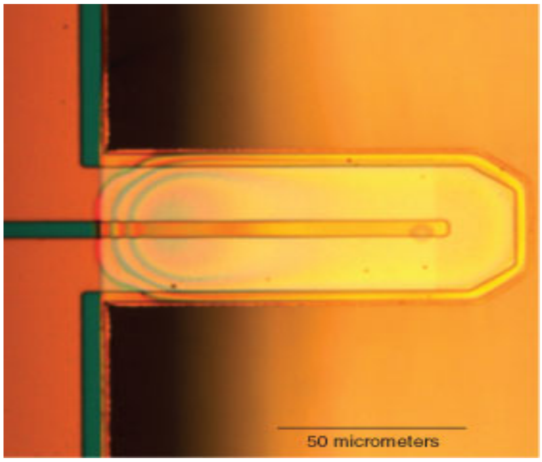
As transducers, microcantilevers rely on their flexibility or elasticity to create some type of measurable change when exposed to external stimuli. The cantilever's reaction to an external stimulus is referred to as *mechanical stress*. This stress results in a change in one of the cantilever's mechanical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

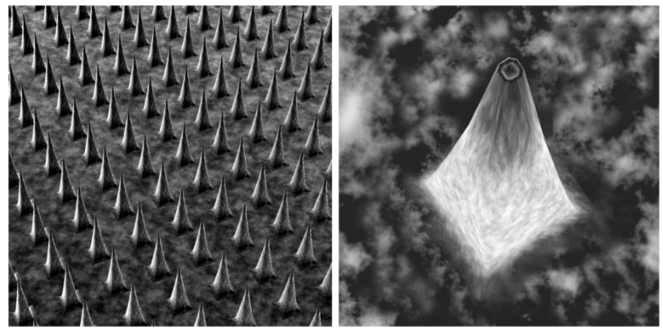
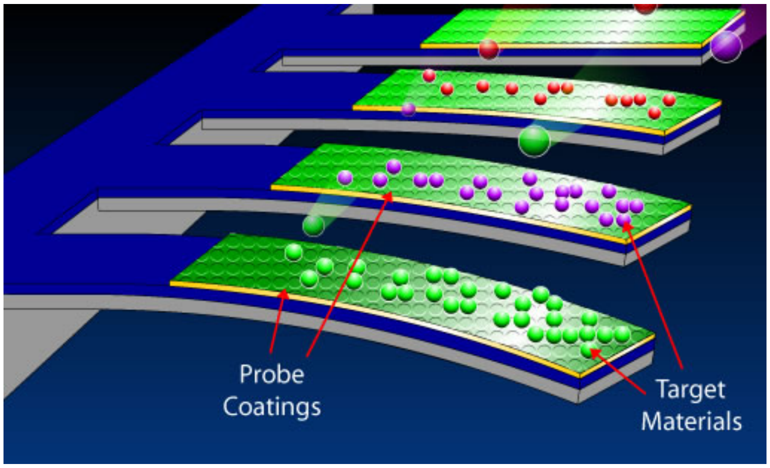


*Illustration of a MEMS Needles array with close-up of a needle's tip*

**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**

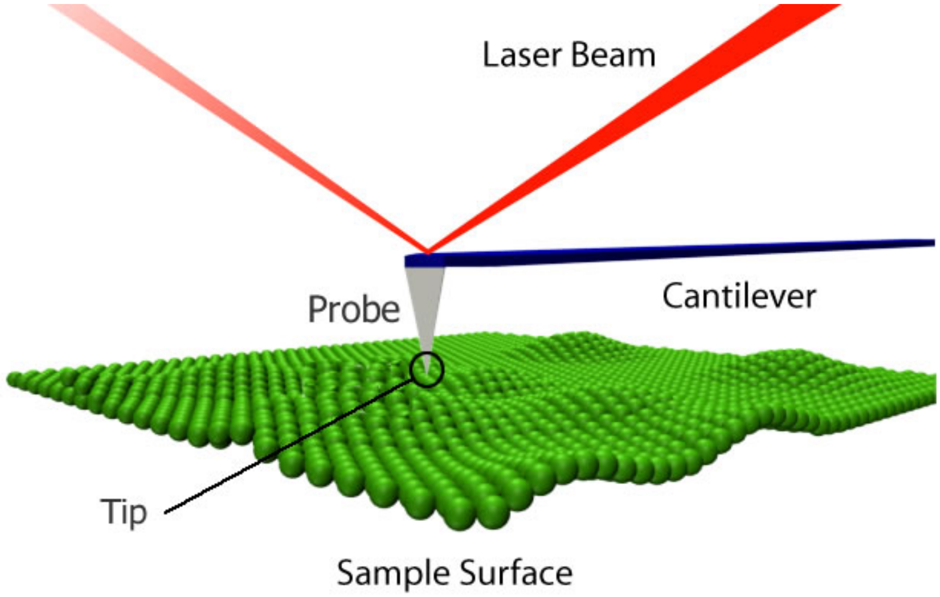
There are several advantages to using microcantilevers in sensors:

- 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.

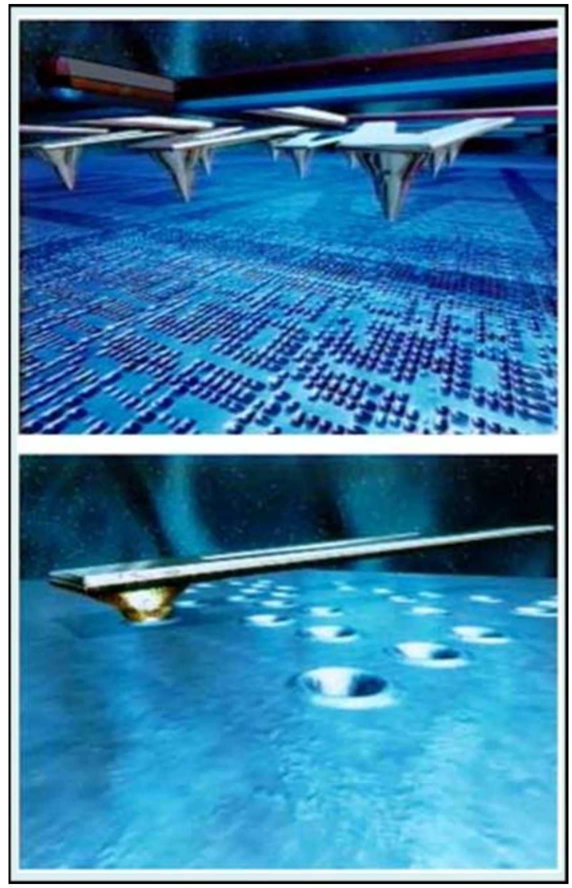
(*For more information on AFMs, see the SCME unit on Atomic Force Microscopes.)*

**Cantilevers as Transport Devices: Read/write storage**

Microcantilevers 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.

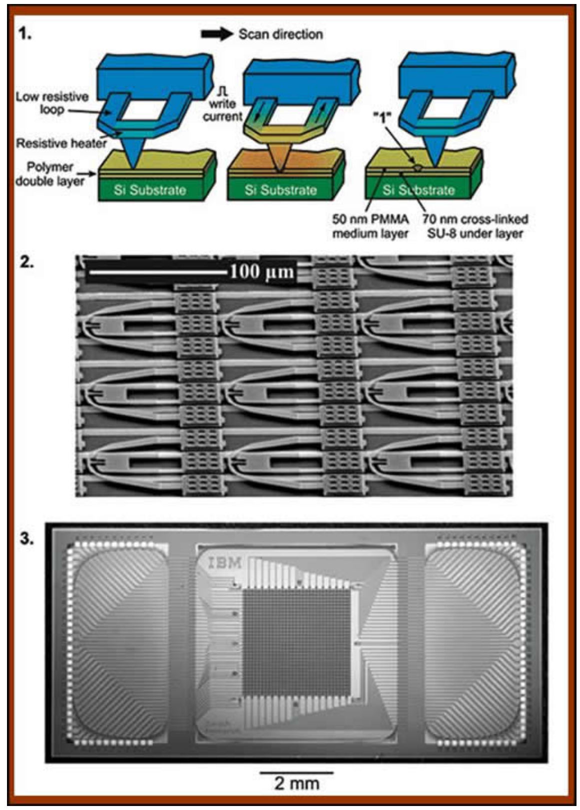


*IBM Millipede - Close-up of read/write cantilevers[3]*
*[Photo courtesy of IBM]*

## 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]

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]




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

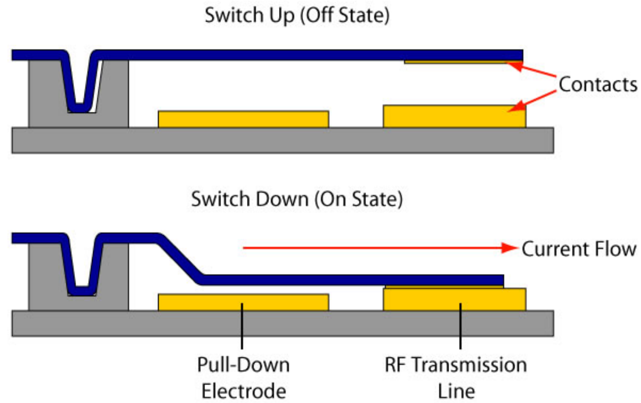
## Microcantilevers as Switches

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.

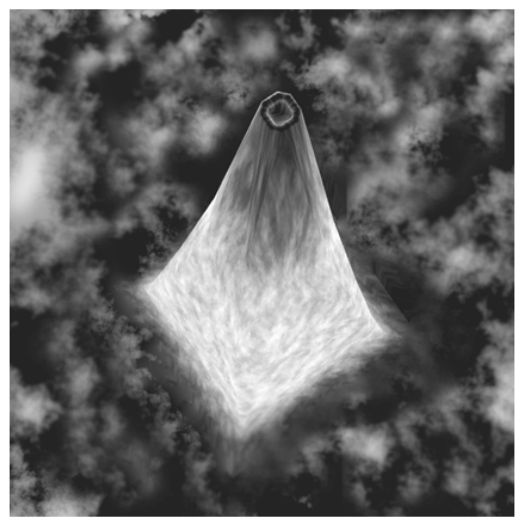



*MEMS RF Switch*

**Microcantilevers as Needles**

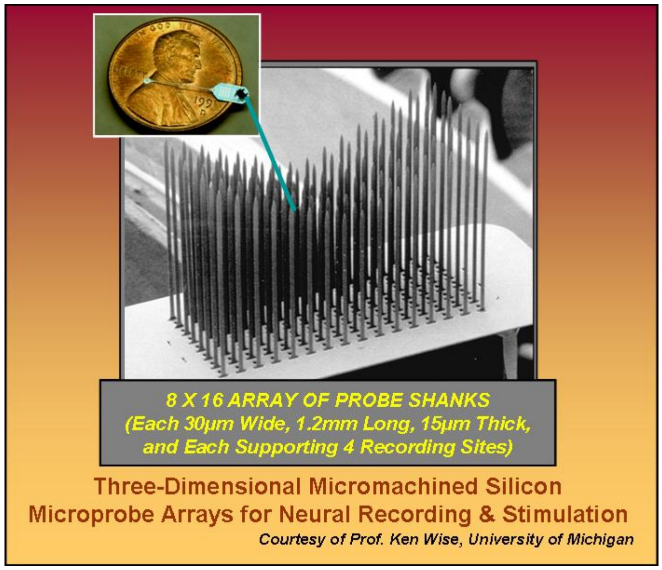
In the medical field, micro and nano-sized cantilevers are being used as needles and as probes for diagnostics, therapeutics and research.

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




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?*

5. *View the YouTube video "MEMS Applications" [https://youtu.be/ebnpmf3kOq4] (13:37minutes). While watching the video identify possible applications for microcantilevers.*

**Summary**

Microcantilevers 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 microcantilever is a cornerstone component used in a wide variety of microsystems including micro-chemical sensor arrays, atomic force microscopes, microswitches, and neural probes.

**References**


1. "What is an Atomic Force Microscope?" Department of Chemical and Environmental Engineering. University of Toledo.
2. ""Millipede" small scale MEMS prototype shown at CeBIT." Nano Tsunami. Rüschlikon, 3 March 2005. http://www.voyle.net/MEMS/MEMS%202005/MEMS%202005-0006.htm
3. "IBM's Millipede Project Demonstrates Trillion-bit Storage Density". IBM Research. Zurich. June 11, 2002.
4. "IBMs Millipede Memory Chip". IEEE Global History Network. September 2008.
5. "Atomic Force MEMS Memory". 2006 IEEE International Electron Devices Meeting. Paper #32.l ("Thousands of Micro-Cantilevers for Highly Parallel and Ultra-Dense Data Storage," P. Vettiger et al, IBM Research)
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 Interface with a silicon neural probe in the advancement of microtechnology". Seung Jae Oh, Jong Keun Song, Sung June Kim. Biotechnology and Bioprocess Engineering. 01/2003; 8(4):252-256.

## 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 object 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 Activity: Resonant Frequency vs. Mass

## Disclaimer



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