
How Does a Cantilever Work?

Primary Knowledge Instructor Guide

Notes to Instructor

How Does a Cantilever Work? is one of the primary knowledge units for the Microcantilever Learning Module. It is recommended that this unit follow the Microcantilever Applications Overview.

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 or microelectromechanical systems (MEMS). 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



The Diving Board - A Common Cantilever

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.

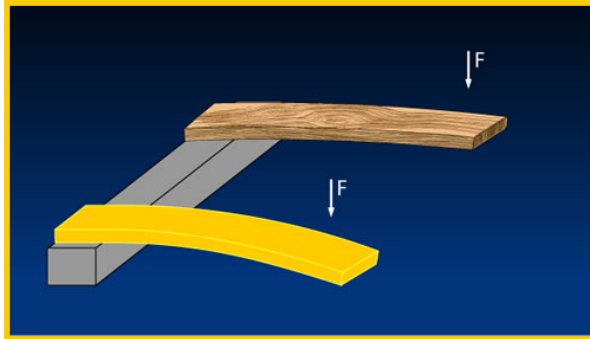
This unit covers the theory of how a cantilever works. It will identify differences in the operation of macro and microcantilevers.

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).

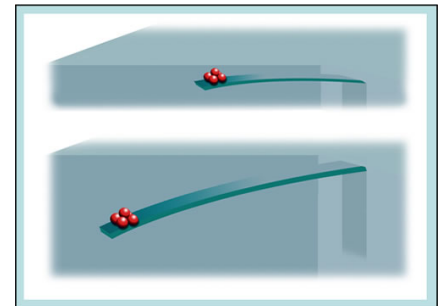


Comparison in the bending of wood and polypropylene cantilevers under the same load (F)

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 right*).



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?

Microcantilevers

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

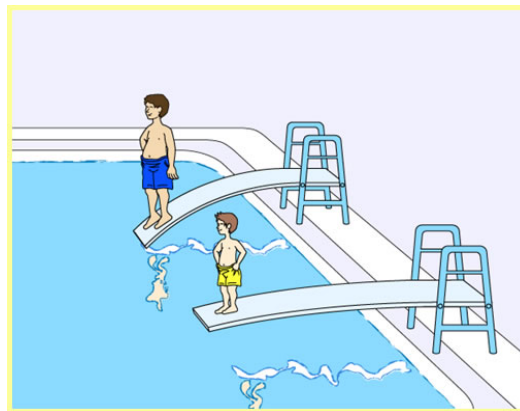
Microcantilever Modes of Operation

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 macrocantilevers 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.

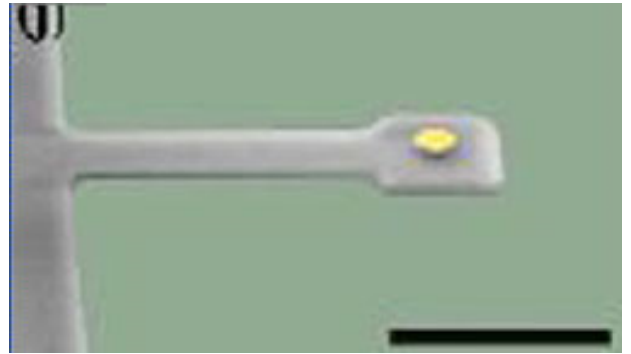
In microapplications this displacement is due to one of two factors:

- 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

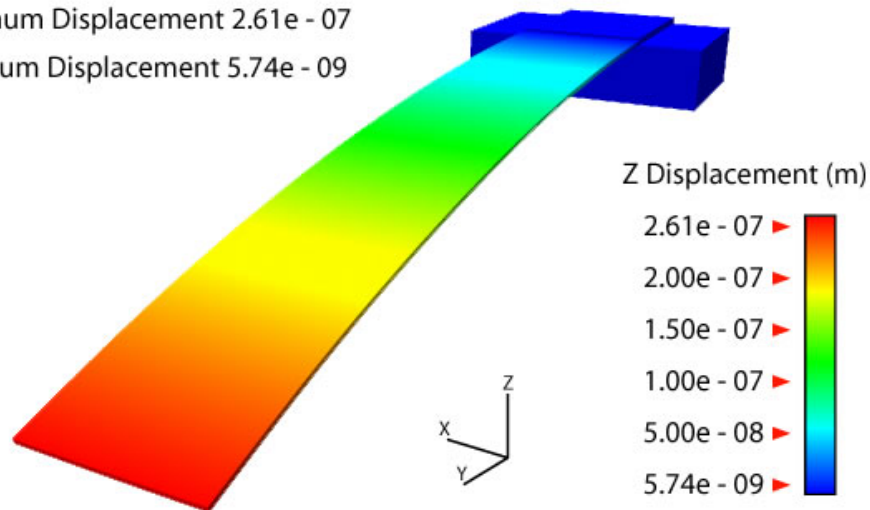
is large enough to indicate a change in mass as small as a few nanograms or a surface stress of several 10^{-3} N/m (as indicated in the following image).¹

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

Maximum Displacement 2.61×10^{-7}
Minimum Displacement 5.74×10^{-9}

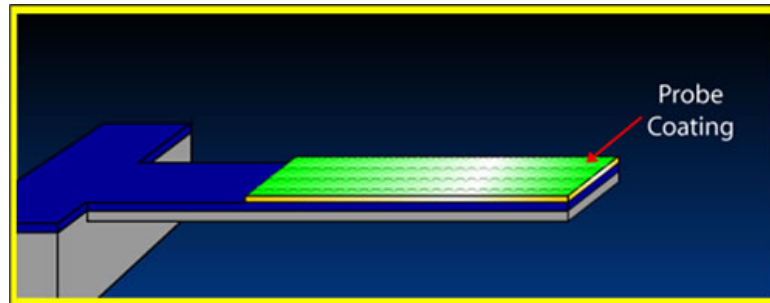


A finite element analysis (FEA) model showing Microcantilever Displacement under Stress

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

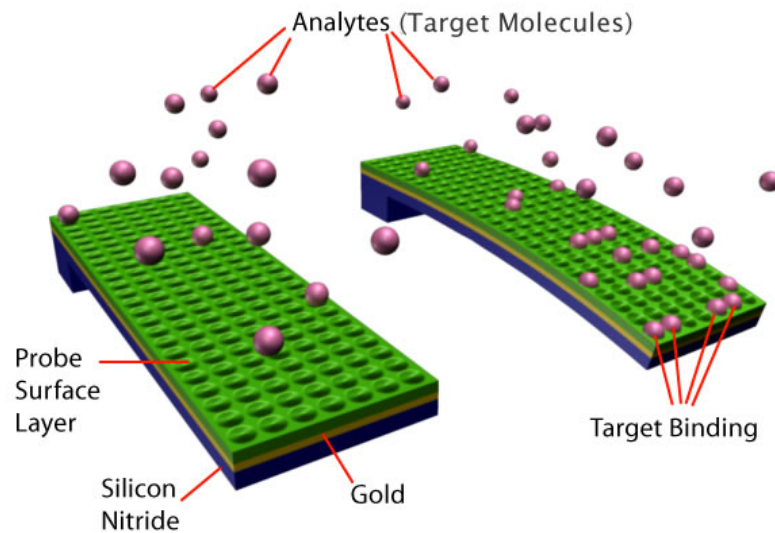
One of the primary applications of microcantilevers is in the environmental and biomedical fields. Chemical sensors incorporate microcantilevers as transducers. Chemical sensors detect, analyze, and measure specific particles (molecules or atoms) within gas and liquid environments. These particles are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

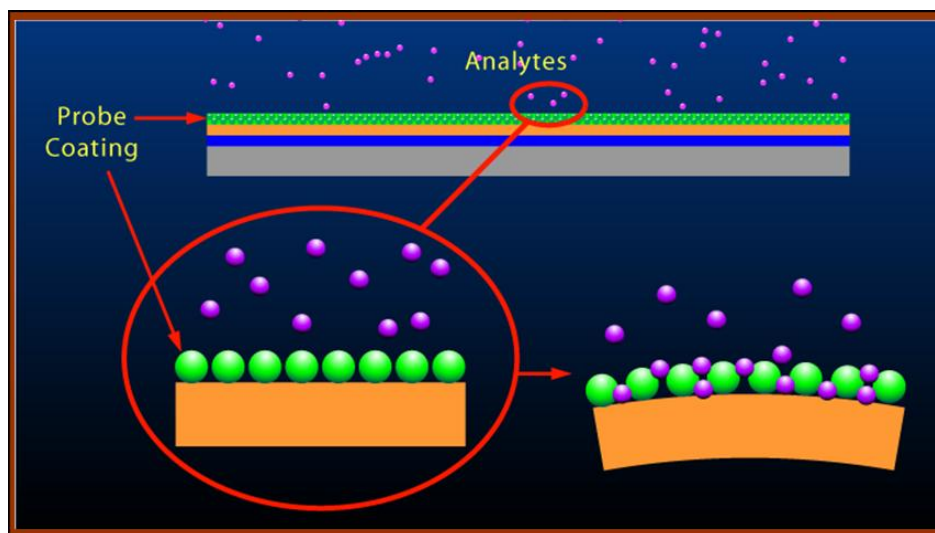
Surface reaction is when the analytes are confined to the surface of the probe coating. The figure shows the probe coating as a monolayer of probe molecules attached to a gold layer of the cantilever. The reaction is chemisorption of the analytes on the cantilever's surface (the probe molecules). Notice 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.

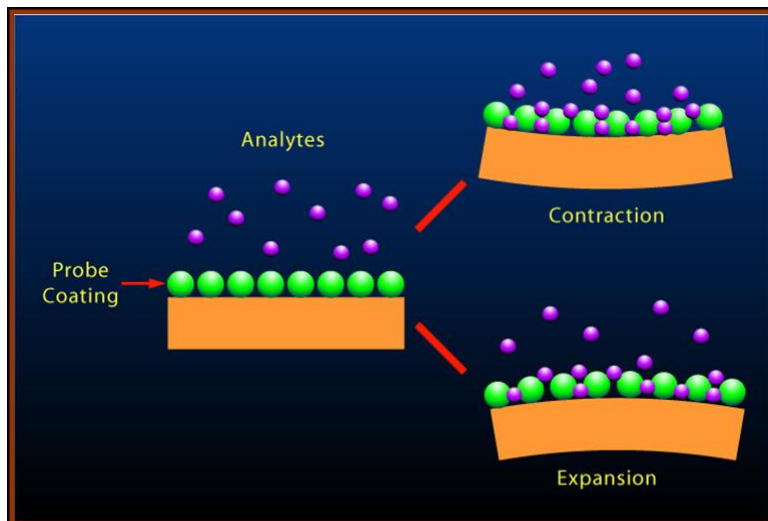
An example of this mechanical stress is the reaction of two different metal strips bonded together and heated. Each metal has a different coefficient of thermal expansion. When heated, one metal expands more than the other. Since they are bonded together, this difference in expansion causes the bonded 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



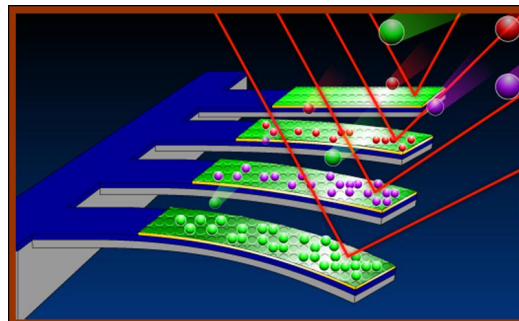
Expansion and Contraction of Probe Coating

In microcantilevers, surface reaction (analytes being adsorbed at the surface) is not the only reaction that can take place. Analytes can also be absorbed into the bulk of the probe coating, much like the absorption 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:

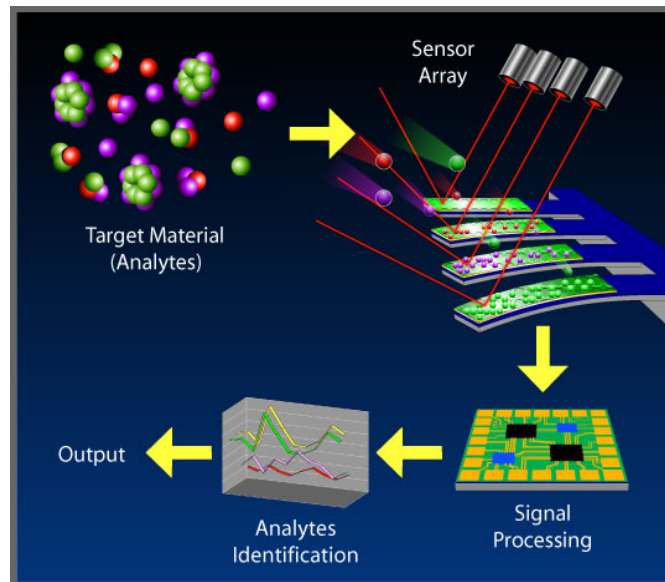
- Change in Angular Deflection (Δ angular deflection)
– Reflective material is embedded as a layer onto the surface of the cantilever. A laser beam is directed to and reflected from the cantilever's surface creating a reference angle of deflection (*see figure*). As the cantilever bends the change in 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 dedicated 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

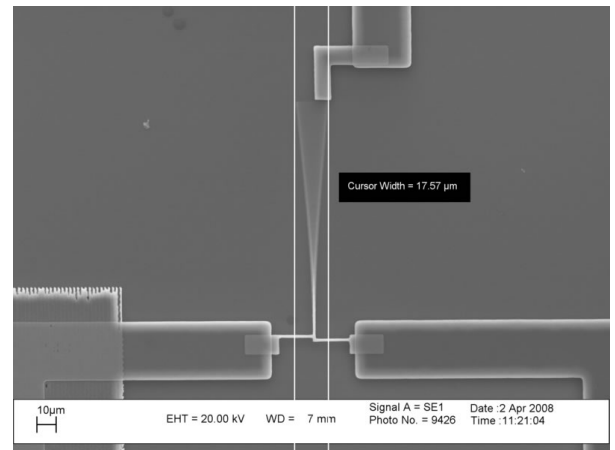
Chemical sensors also use the dynamic mode of operation to detect and measure specific target materials. Just like the static mode operation, dynamic sensors can consist of one microcantilever transducer or an array of transducers.

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)

To see this in action, view this YouTube video: **Cantilevers and Resonant Frequency**
[<https://youtu.be/K1U23NQXQlo>]

A Bit of Dynamic Theory

$$\omega_0 = \sqrt{\frac{k}{m}}$$

Natural Frequency

$$k = \frac{Et^3w}{4l^3}$$

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)

So what do you think? (Answers)

1. Which yields the higher frequency – a lower mass or a higher mass cantilever?

Answer: Lower mass

1. Which yields the higher frequency – a short cantilever or a long cantilever?

Answer: Short cantilever

2. Which yields the higher frequency – a thin cantilever or a thick cantilever?

Answer: Thin cantilever

3. Which cantilever material yields a higher frequency – wood or metal, glass or metal? (Assume the same cantilever dimensions)

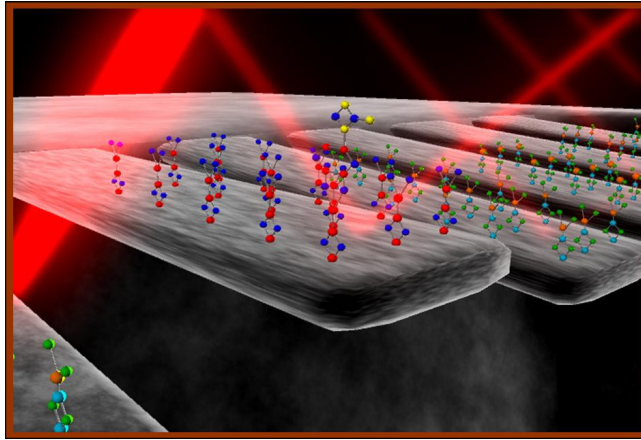
Answer: Wood or metal (wood); glass or metal (depends on the metal)

4. What is the spring constant and natural frequency for a poly crystalline silicon cantilever with the following properties:

- a. 2 microns thick
- b. 20 microns wide
- c. 100 microns long
- d. Polycrystalline silicon density approximately 2.330 kg/cm³

Answer: Resonant is about 132 kHz, k is about 6.4 kg/s²; mass of the cantilever is about 9.32x10⁻¹² g

An Application of Dynamic Mode Transducers



Dynamic Mode Microcantilevers

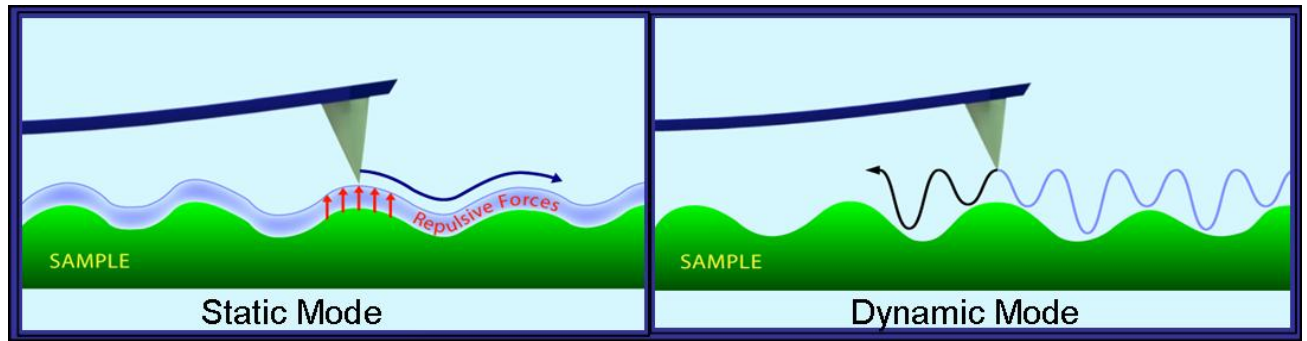
Dynamic microcantilevers are also used as the transducers for Chemical Sensor Arrays (CSA). In a dynamic CSA, the cantilevers are initially excited by piezoelectric, magnetic, electrostatic or thermal actuation. This input causes the cantilevers to oscillate at their resonant frequencies. When analytes 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.

Watch this YouTube video to see this biosensor in action: **Microcantilevers as Biosensors**
[<https://youtu.be/rPJ0QMxcbs>]

[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."*)

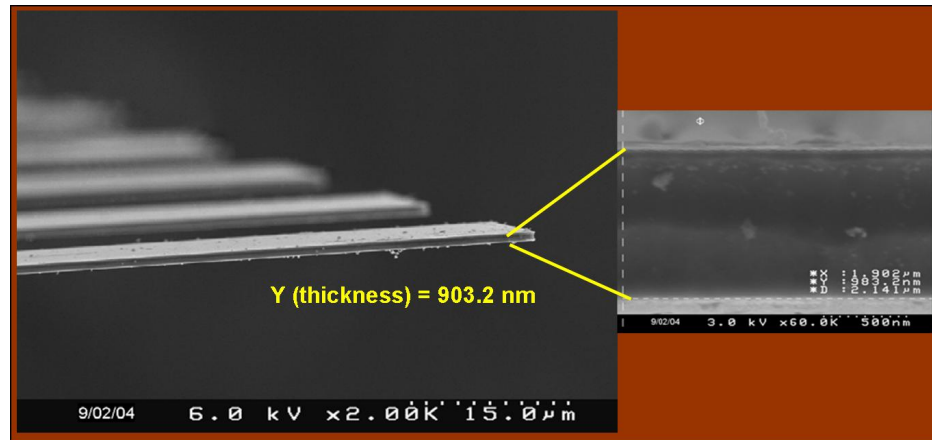
Review Questions

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.

Note to Instructor

It is recommended to follow this unit with the Cantilever Activity: Resonant Frequency vs. Mass. This would provide the participants with a better understand of the dynamic mode of operation.

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

- Microcantilever Applications
- Cantilever Activity: Resonant Frequency vs. Mass
- Terminology and Research on Microcantilevers
- 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>

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