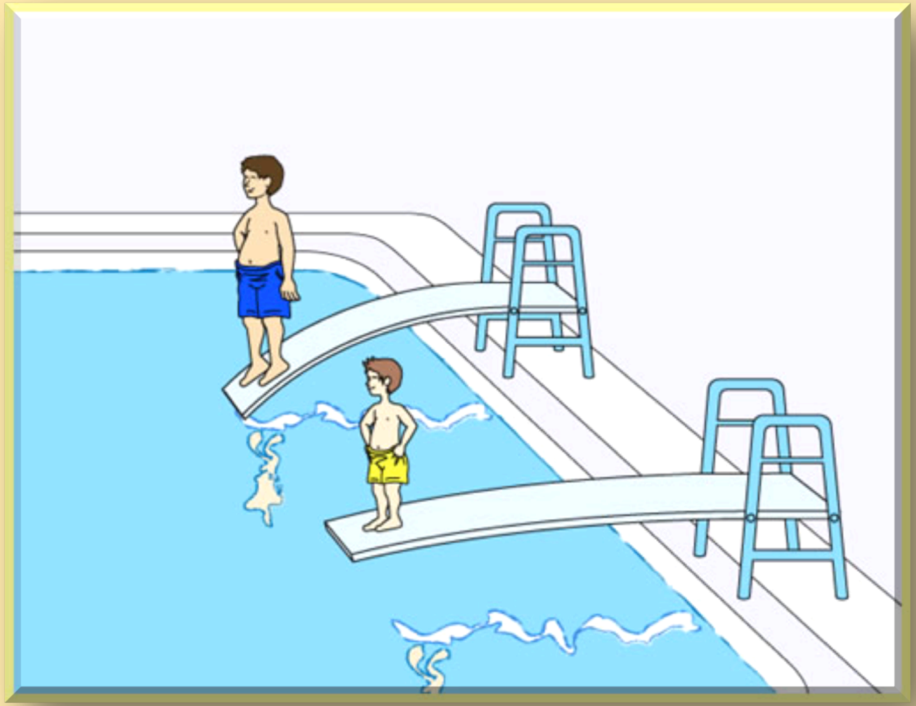
# HOW DOES A CANTILEVER WORK?



# Unit Overview

The microcantilever is a widely used component in microsystems devices.  Its flexibility and versatility make it a popular component for a number of applications.

This unit provides information on the basic characteristics of cantilevers and how these characteristics affect the operational characteristics 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.

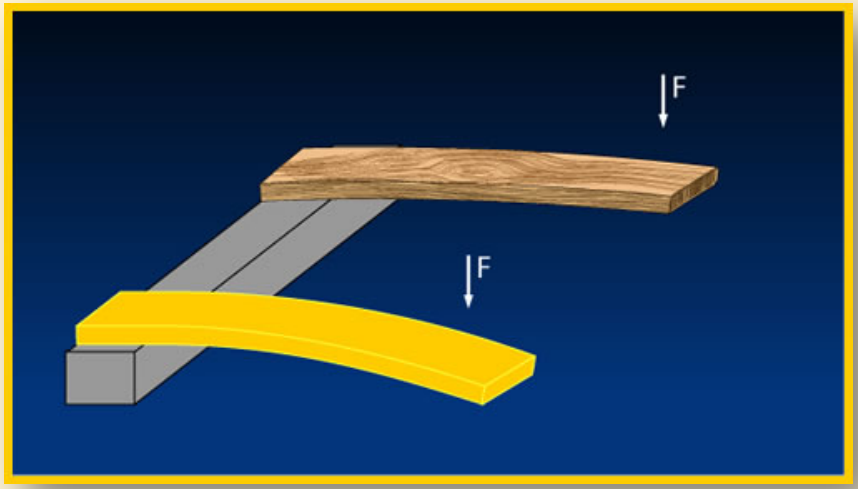
# Introduction

- A cantilever is a beam constrained at one end with the other end extending freely outwards.
- Cantilevers are built for rigidity (balconies) and flexibility (diving board).
- In microsystems flexible cantilevers are used in applications where an external stimulus causes the cantilever to flex or bend or oscillate.
- More rigid cantilevers are used as a transport device.

*A Diving Board Cantilever*

# Cantilever Properties - Materials

- Geometric shape and material determine a cantilever's stiffness.
- Here we illustrate two cantilevers of the same dimensions but different materials - oak and polypropylene.
- Oak has more than five times the stiffness of polypropylene; therefore, oak would bend less than polypropylene under the same load (F).




*Deflection of a wood and polypropylene cantilever under the same stress (F)*

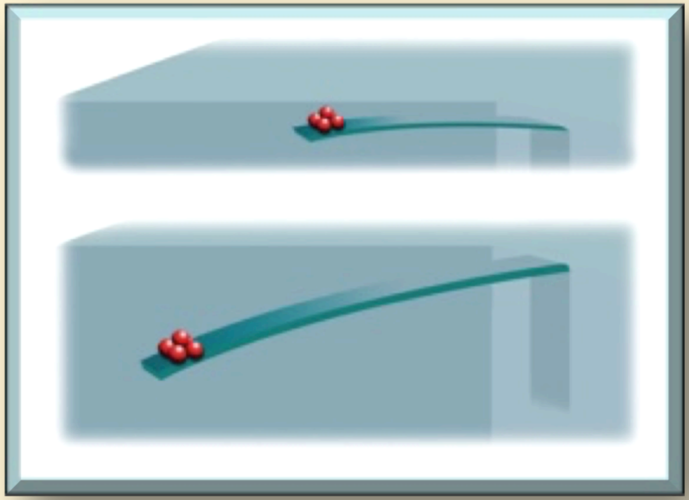
# Cantilever Properties: Dimensions

Dimensions: length, width and thickness.

A short cantilever is stiffer than a long cantilever of the same material, width and thickness.

In macroapplications, short cantilevers are used for balconies, longer ones for diving boards.

In microapplications, short cantilevers work best as a latch,  long ones as a transducers.



*Cantilever length vs. weight*

# Cantilever Properties: Review

- *What macroapplications use a "short" cantilever?*
- *What macroapplications use a "long" cantilever?*
- *In microapplications, which cantilever would work best as a latching device – 10 microns long or 100 microns long?*
- *In reference to the width of a cantilever, what are two applications where one application requires a narrower cantilever than another?*

# 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

# Modes of Operation – Static vs Dynamic

- Static mode - Cantilever is in a static state. Displacement of the cantilever due to a load or intrinsic stress generated on or within the cantilever is measured.

- Dynamic mode – An external actuation causes the cantilever to oscillate at its natural (resonant) frequency. Any change in the load or mass of the cantilever results in a change in frequency. The change in frequency is measured.

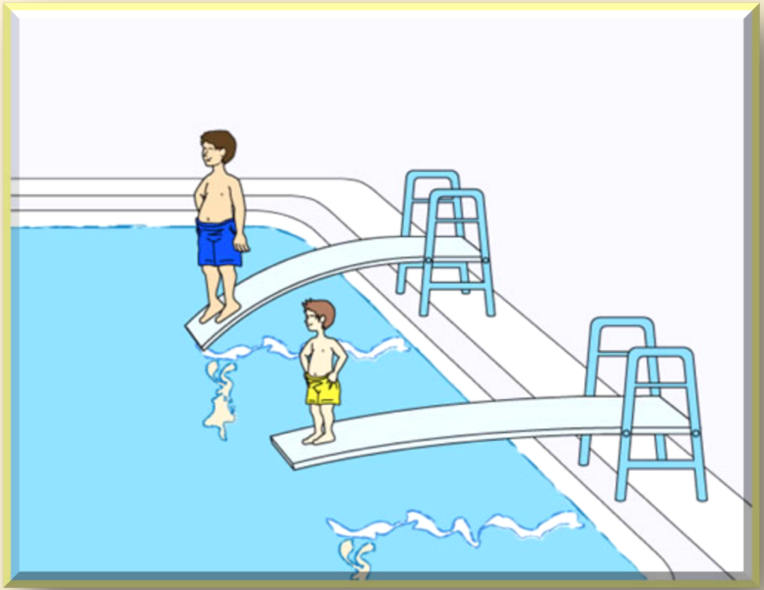
# Static Mode

In the static mode, a change in the cantilever's z-displacement indicates a change in load or intrinsic stress.

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, the greater the displacement or bend.



# Static Mode of Cantilevers

In microapplications this displacement is due an

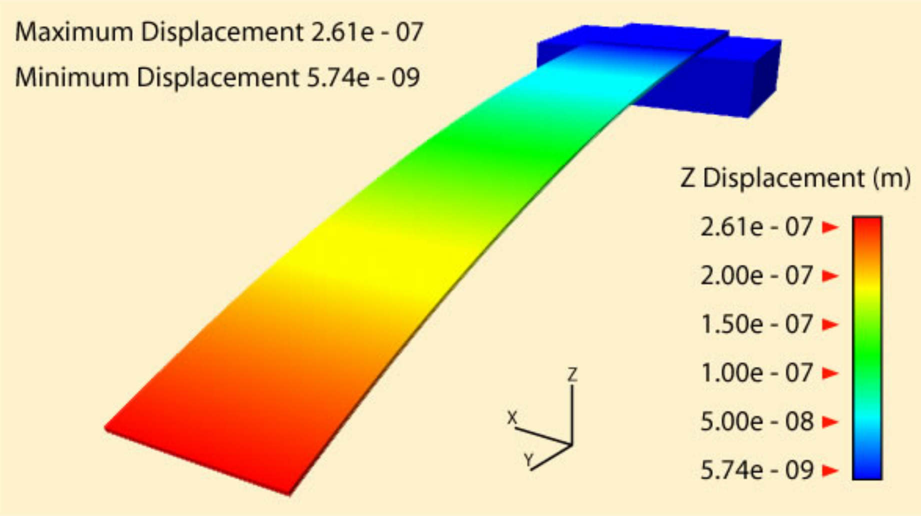
- external load or force or
- intrinsic stress.

In the macro-world, this displacement would be considered negligible.

In the micro and nano 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. *(See figure below)*

***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]*

# Microcantilevers as Transducers




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

Static mode measures the amount of cantilever displacement. Diagram illustrates the displacement of a microcantilever due to a thermal stress on the cantilever's surface.

The maximum displacement at the suspended end is *255 nm.*
*(This is more than enough to be measured in the microscopic world.)*

# Nanodisplacement

Nanotechnology has enabled the design and fabrication of nanocantilever sensors capable of measuring even smaller displacements, such as a

***10 nm displacement due to a surface stress of several $10^{-3}$ N/m!***

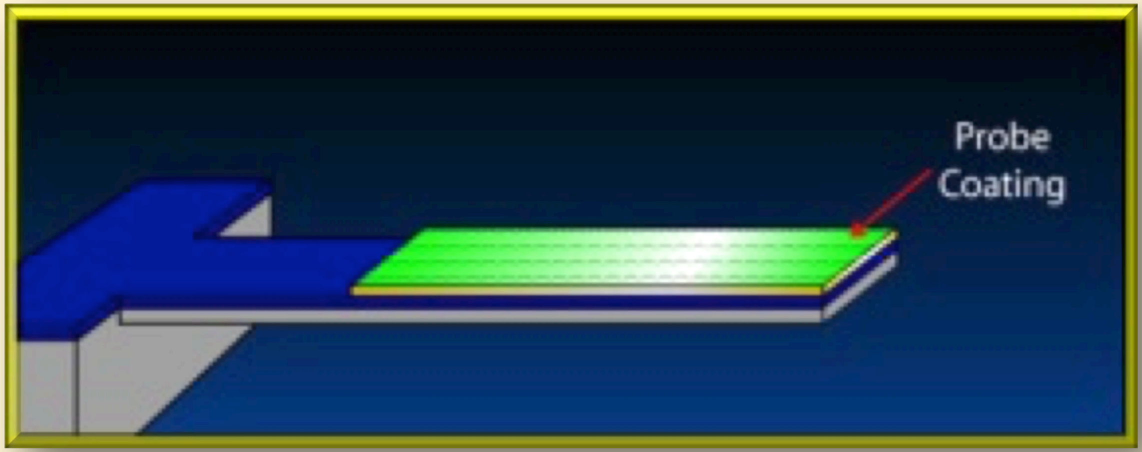
# Microcantilevers in Sensors

One of the primary applications of microcantilevers is as transducers for chemical sensors in the environmental and biomedical fields.

Chemical sensors are used to 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.

# Microcantilever Transducer




*Probe Coating for Cantilever Transducer*

A microcantilever transducer is fabricated with a chemically sensitive coating (probe coating) on one or both surfaces.

This coating provides specificity for molecular recognition.

Different coatings provide different chemical reactions.

# Surface Reaction - Chemisorption

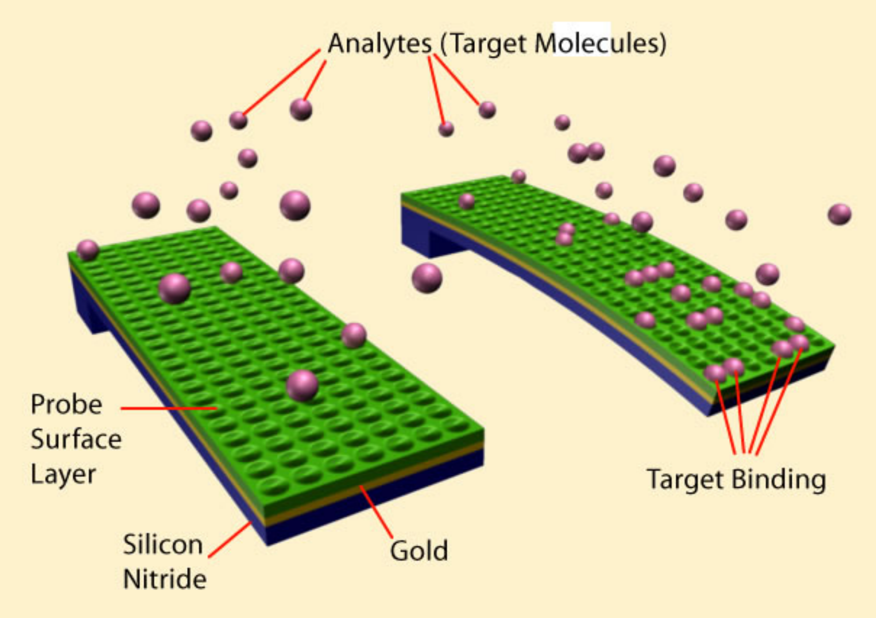
A surface reaction occurs when analytes are captured and confined to the probe coating.

Reaction is chemisorption.

The reaction causes thermal expansion of the probe coating.

In this illustration, the gold layer is not experiencing the same thermal expansion as the probe.

This mismatch results in a bending of the cantilever.

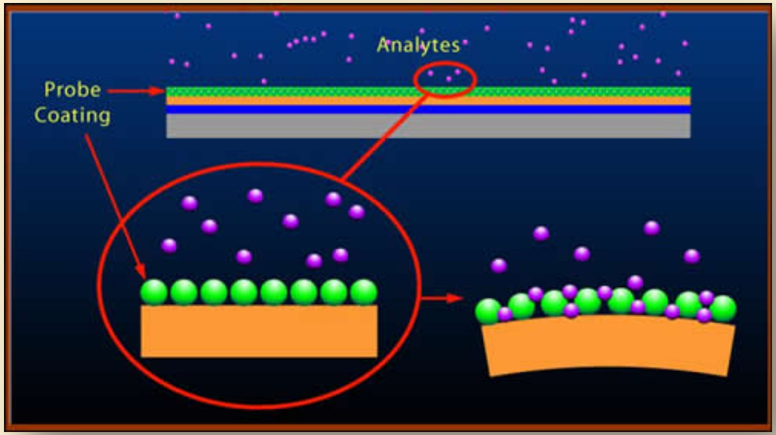



*Surface Reaction between Analytes and Probe Coating Molecules*

# Gravity is not a Factor

Microcantilevers are not affected by gravitational force.

Deflections are related to asymmetric expansion or contraction of the layers caused by the chemical reactions with the analytes and the probe coating.




*Expansion due to Varying stress on Dissimilar Layers*

In the figure, two different layers (a probe layer bonded to a gold layer) do not react in the same manner.

The thermally induced stress caused by the reaction between the analytes and the probe results in different rates of expansion and a bending of the cantilever.

# An Example of Mechanical Stress

You have a bi-metallic strip that is made of two different metals bonded together lengthwise.

*What happens when you heat the metal strip?*

# An Example of Mechanical Stress

You have a bi-medal strip that is made of two different metals bonded together lengthwise.

*What happens when you heat the metal strip?*

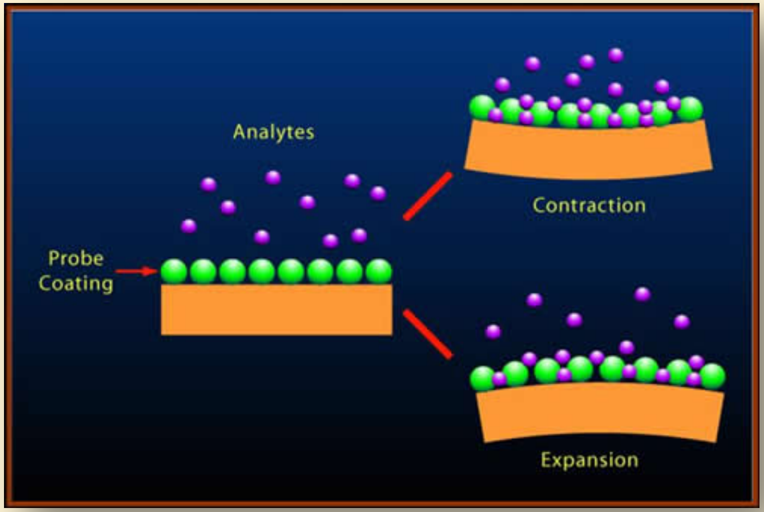
**Because each metal has a different coefficient of thermal expansion, one will expand more than the other. This causes the strip to bend. The direction it bends depends on which metal expands the most.**

# Chemical Reaction - Molecular Sponge

Like water into a sponge, analytes can be adsorbed at the surface as well as into the bulk of the probe coating.

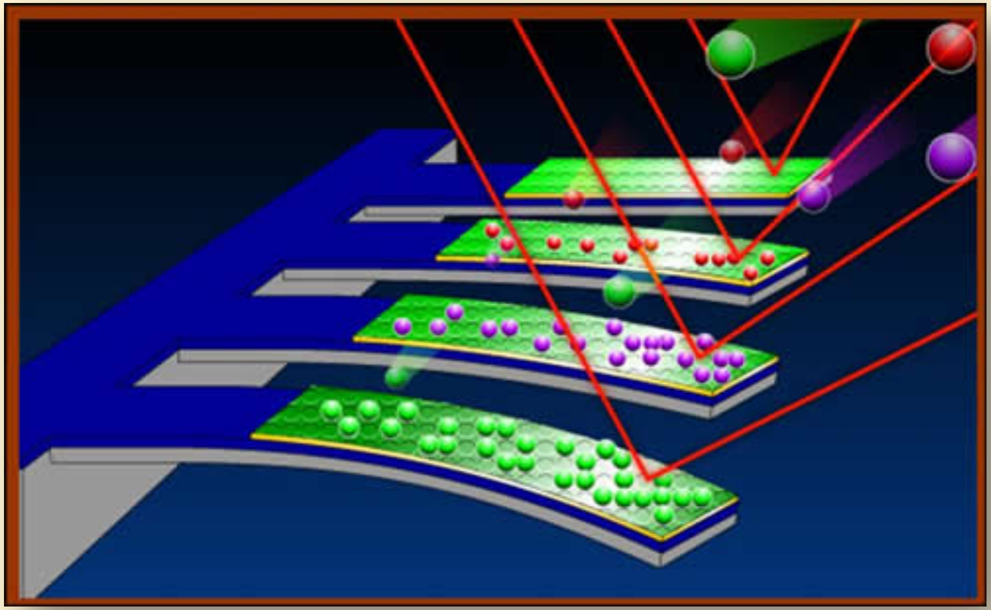
This reaction can cause the coating to contract creating an upward bend in the cantilever.

This reaction can also cause the coating to expand creating a downward bend in the cantilever.




*Expansion and Contraction of Probe Coating*

# Measuring Displacement



***Measuring Displacement using changes in Angular Deflections***

*Notice the angular deflection of the beam off the back cantilever. This is the reference cantilever and thus the reference angle. It will remain constant as there is no probe coating on this cantilever.*
*As the "bends" of the probe cantilevers increase, so do the angular deflection.*

<u>Angular Deflection</u> – A laser beam is reflected off reflective material below the cantilever's surface creating a reference angle. As the cantilever bends the change in the angular deflection is measured.

# Measuring Displacement

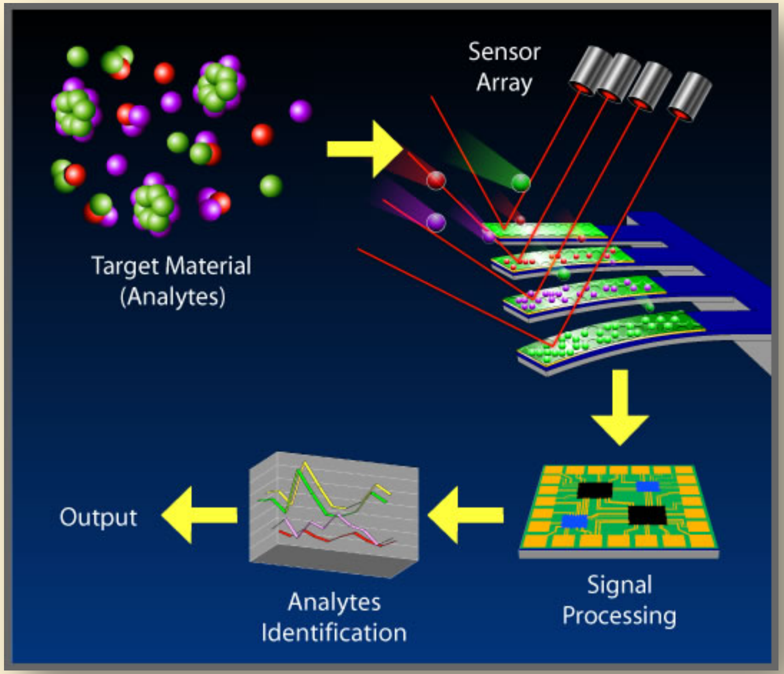
<u>Resistance </u>- A piezoresistive material layer is embedded within the cantilever.  As the cantilever bends, a change in resistance is measured.

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

# Application of the Static Mode

A Chemical Sensor Array (CSA):

- Each transducer is coated with a probe coating.  Analytes are adsorbed by specific coatings.
- Surface stress causes a minute bending. The more analytes adsorbed, the greater the bend.
- The change in angular deflection is detected and recorded.
- The data is processed.
- The types of analytes are identified.




*Chemical Sensor Array*

The concentration of each analyte correlates with the amount of change in the angular deflection of its respective laser.

# Dynamic Transducers

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

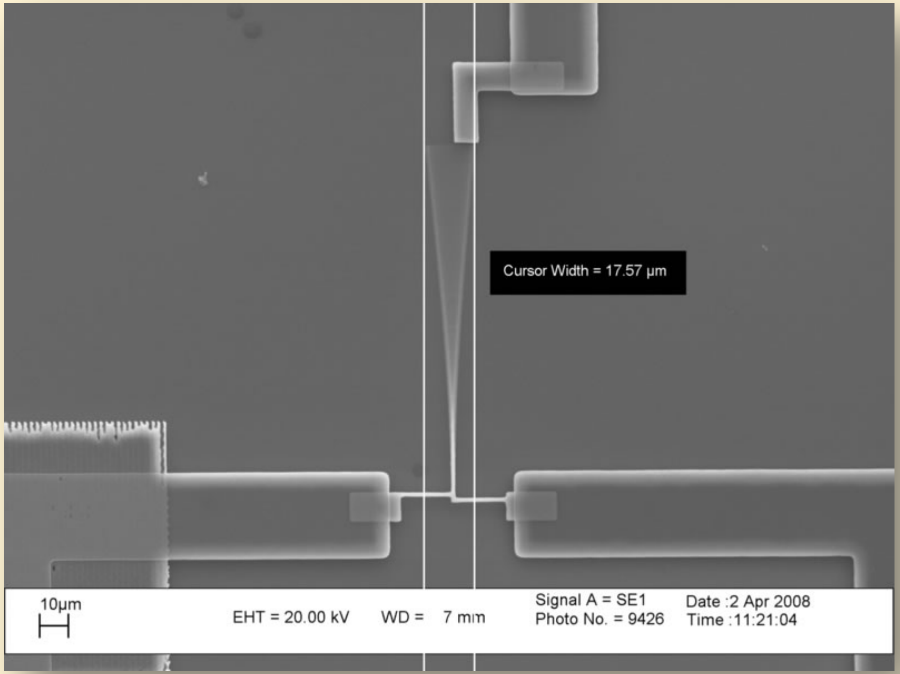
# Resonant Frequency

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 resonant frequency, it is said to be in "resonance".

As the mass of the system changes, so does the resonant frequency.




***Microcantilever in Resonance***
***This image is a MEMS microcantilever resonating in a Scanning Electron Microscope (SEM)***

# Change in Resonant Frequency

- When a baby bounces on the end of a diving board the diving board oscillates at a frequency determined by the diving board characteristics and the mass of the baby.
- 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.

*Which would result in a higher resonant frequency – the baby or the baby and the father?*

# Watch the Animation – Are you correct?

“Save my baby diving board resonance” SCME Animation - YouTube

# A Bit of Dynamic Theory

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

Natural Frequency

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

Spring Constant

The natural frequency ($\omega_0$) of a cantilever is related to its spring constant, k and mass, m.  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*

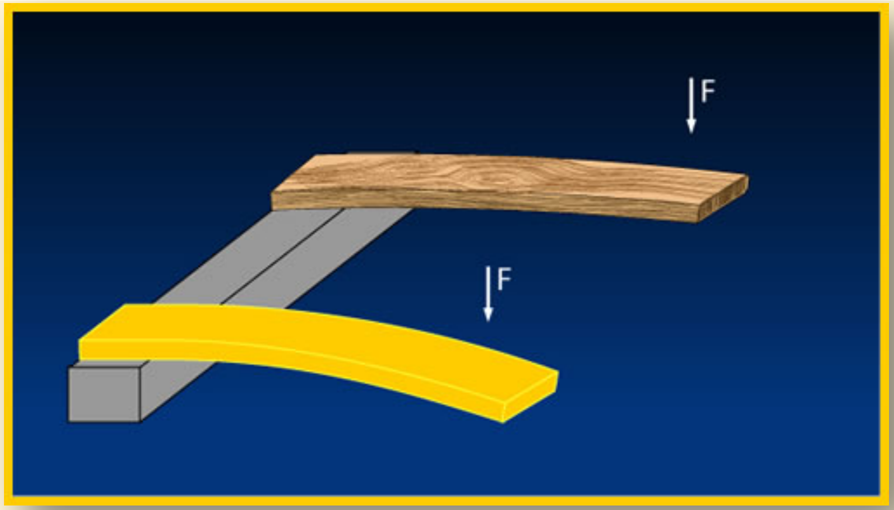
*w  = width*

*l  = length*

# Young's Modulus (E)

The measure of the stiffness of a given material. The stiffer a material is, the higher the *E value in GPa:*

- Rubber: -0.01 to 0.1
- Polypropylene: 1.5 – 2
- Oak wood (along grain): 11
- Aluminum alloy: 69
- Polycrystalline silicon: 160
- Diamond (C): 1050 – 1200




*Elasticity of Wood (brown) vs. Polypropylene (Yellow)*

# So What Do You Think?

- Which yields the higher frequency – a lower mass or a higher mass cantilever?
- Which yields the higher frequency – a short cantilever or a long cantilever?
- Which yields the higher frequency – a thin cantilever or a thick cantilever?
- Which cantilever material yields a higher frequency – wood or metal? (Assume the same cantilever dimensions)

# So What Do You Think?

- Which yields the higher frequency – a lower mass or a higher mass cantilever?
  - *Lower Mass*
- Which yields the higher frequency – a short cantilever or a long cantilever?
  - *Short Cantilever*
- Which yields the higher frequency – a thin cantilever or a thick cantilever?
  - *Thin Cantilever*
- Which cantilever material yields a higher frequency – wood or metal?  (Assume the same cantilever dimensions)
  - *Wood*

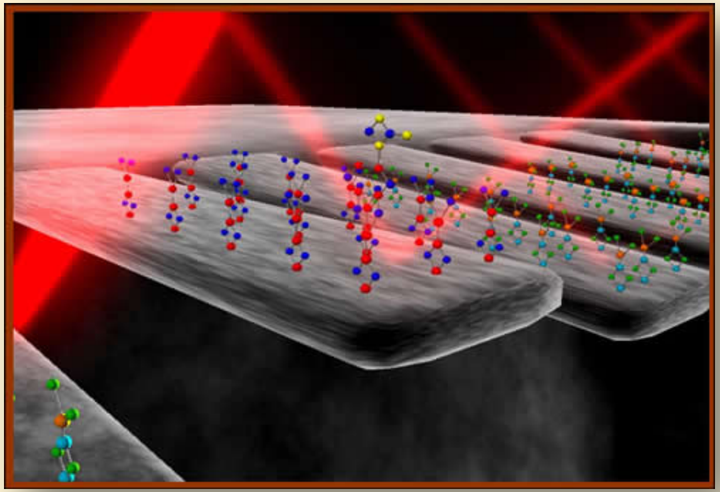
# Applications of Dynamic Transducers

Used as the transducers for CSAs.

As more and more target materials attach to the surfaces, the cantilevers gain mass.

As the mass of a cantilever increases, its resonant frequency decreases.

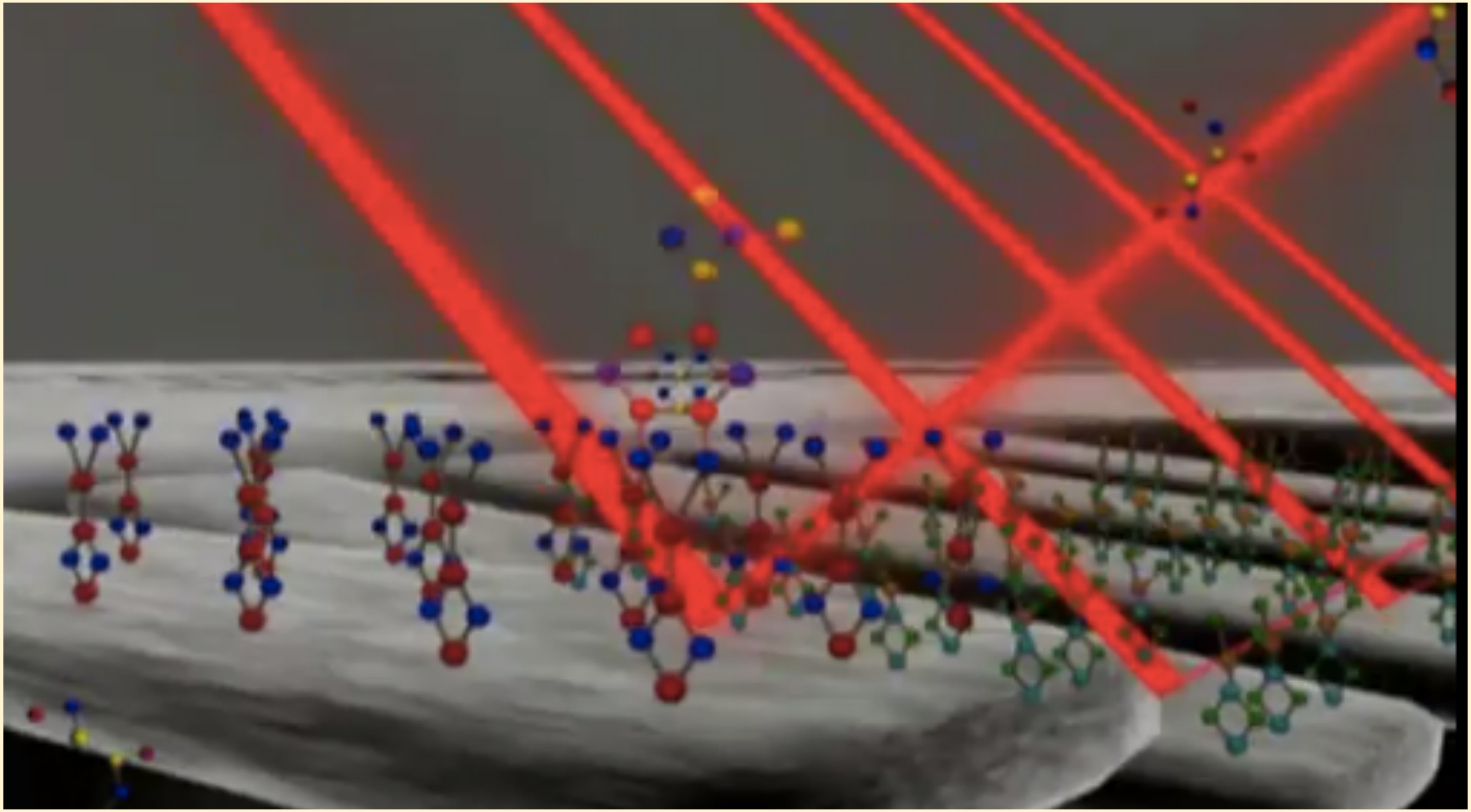
The greater the frequency shift, the greater the amount of accumulated mass.



***Dynamic Mode Microcantilevers***

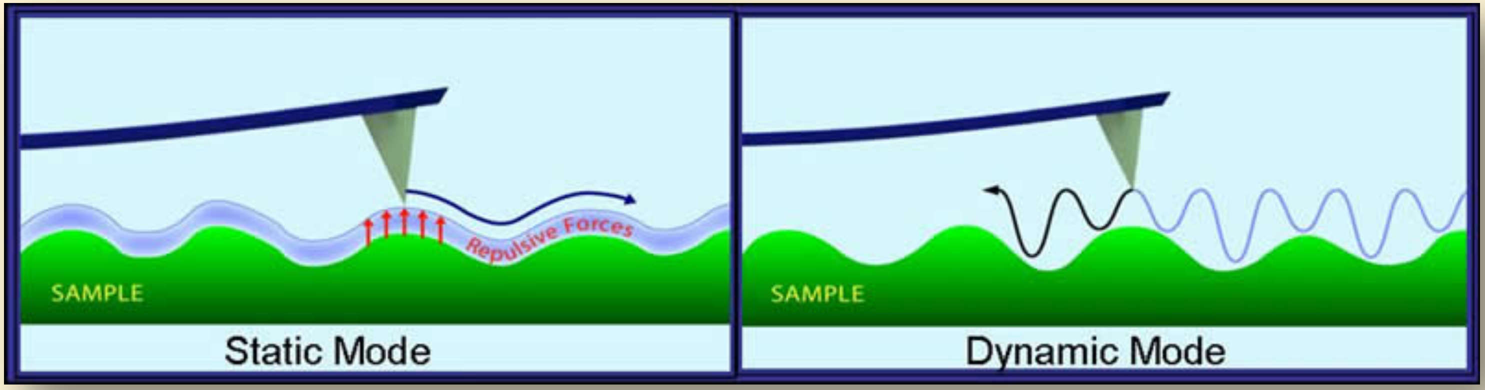
*Let's see how this works.*
*Next slide*

# Dynamic Cantilevers in Action



Cantilever Animation – Microsystems Education YouTube

# Atomic Force Microscope




*AFM - Static and Dynamic Modes of Operation*

Both the static and dynamic modes are used in the Atomic Force Microscope (AFM). In the AFM a microcantilever is used to transport a probe or sensor above the surface of a sample

A static operation is called the "contact mode".

A dynamic operation is called the "oscillating mode“ or “tapping mode”.

# A Little Theory About AFMs

For the microcantilever in an AFM to have the sensitivity needed to map a surface on the nanometer scale, it needs to have a low enough spring constant (k).

A low spring constant allows the microcantilever to respond to very small forces.

The microcantilever must also have a high resonant frequency so that it does not begin to oscillate on its own.

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.  The tip could also come in contact with the sample's surface, damaging the surface.

# An AFM's Spring Constant

- 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 ($\omega_0$) 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.

# Food For Thought

- *How are macro-sized cantilevers similar to micro-sized cantilevers?*

- *How are they different?*

- *What causes a microcantilever to bend?*

# Summary

- Microcantilevers are used in several MEMS applications.
- The specific application determines the microcantilever's dimensions and material.
- The microcantilever is the corner stone component of microsystems, used in sensor arrays, atomic force microscopes, microswitches, needles and probes and more.
- As transducers microcantilevers are operated in the static and the dynamic modes.

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