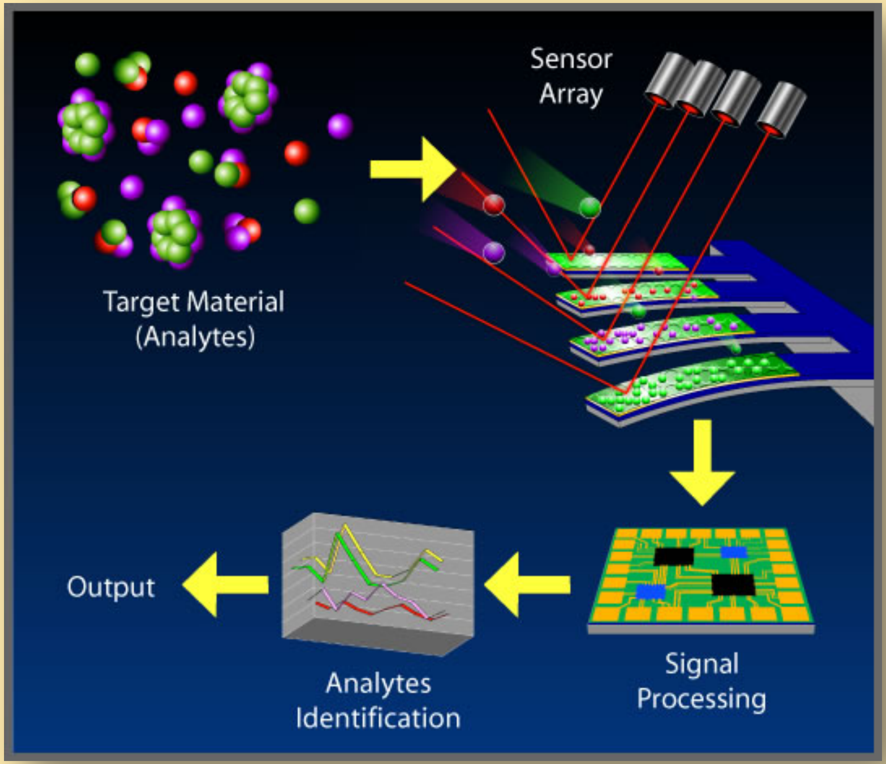
CHEMICAL SENSOR ARRAYS



Unit Overview

Chemical Sensor Arrays (CSA) are MEMS (Microelectromechanical Systems) used to gather, detect, measure, and identify a substance or several substances in a minute sample.

CSAs can be cantilever-based, using micro and nano-sized cantilevers.

This unit is an overview of the operation and applications of MEMS Chemical Sensor Arrays.

Objectives

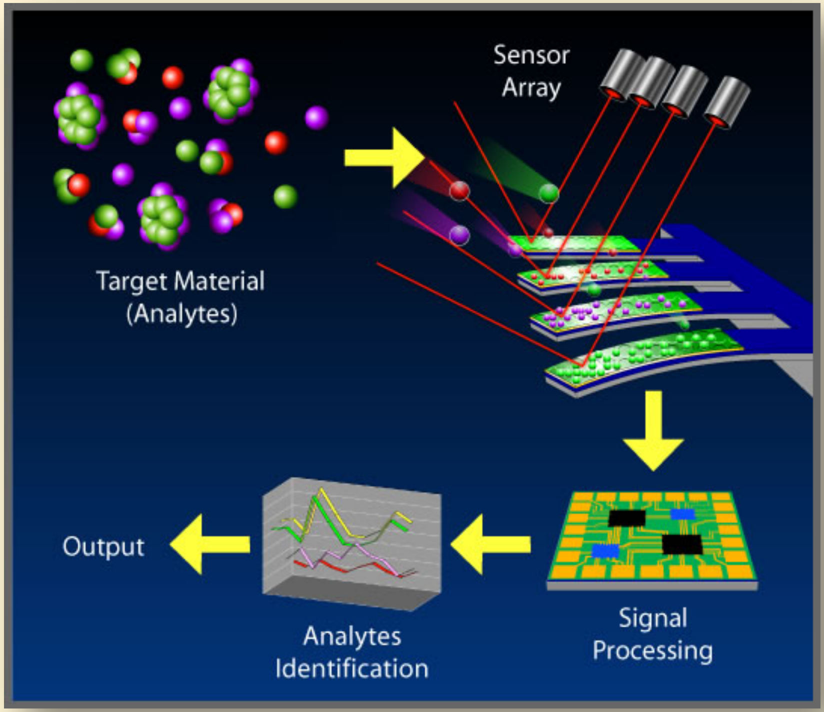
- State at least five applications of a MEMS CSA.
- Compare and contrast the operations of a static and dynamic cantilever-based CSA.
- Describe at least two operating characteristics of a CSA.

Introduction

A CSA is …

- an array of microtransducers and supporting integrated circuits.
- designed to detect and measure the amount or concentration of one or more substances in a sample environment.

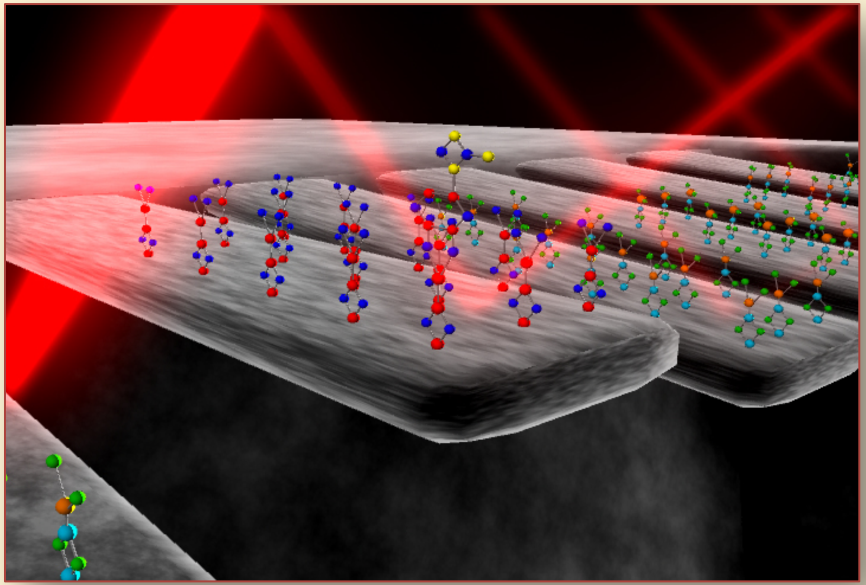
The substances (target materials or analytes) could be specific gas molecules or atoms, antibodies or proteins.



Process flow of a Chemical Sensor Array

MEMS Chemical Sensor Arrays

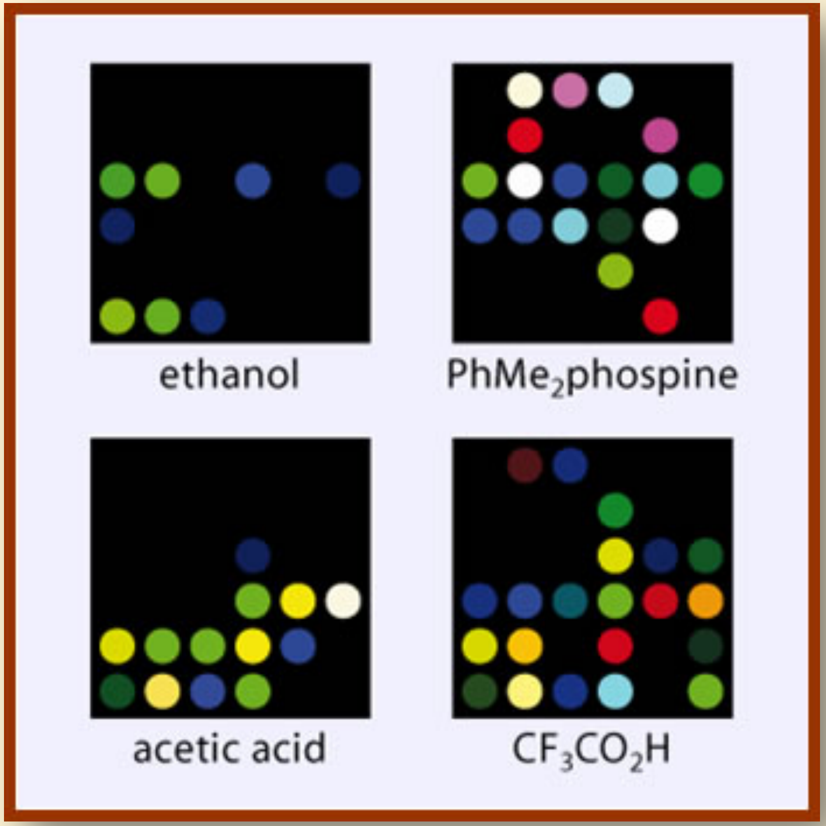
- The micro-size makes a CSA attractive for applications from biomedical to aerospace.
- CSAs can analyze blood samples, detect fuel leaks, analyze a scent or dissect a taste.
- Most MEMS CSAs consist of an array of microcantilever transducers.



Microcantilever Array

CSA Applications

- Medical diagnostics
- Forensics
- Environmental control
- Fragrance design
- Food production
- Security and defense
- Detection of chemical vapors *(see graphic right)*
- Detection of biological agents

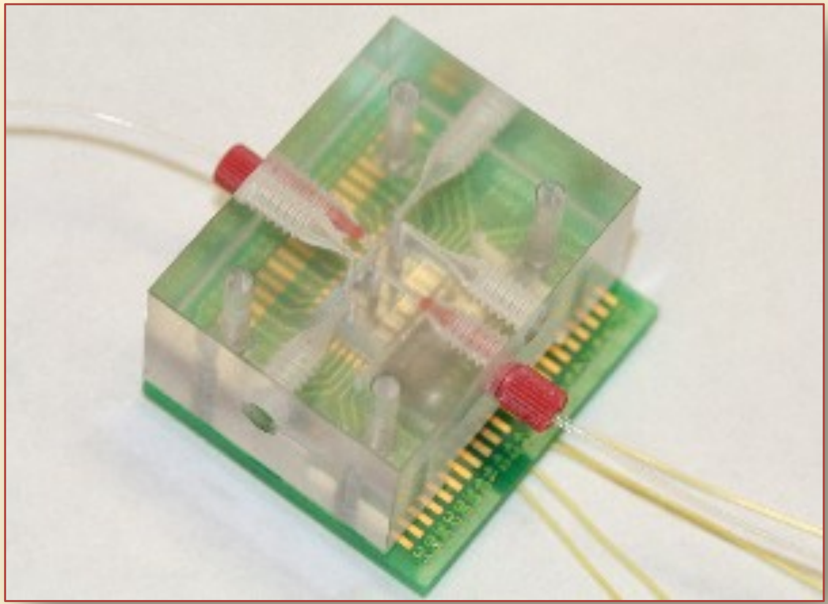


Optical Array for detection of Chemical vapors

Lab-On-a-Chip (LOC) Array

LOC is a MEMS that incorporates several functions on a single chip.

- ❖ Chemical sensing
- ❖ Pumping microfluids
- ❖ Electronics



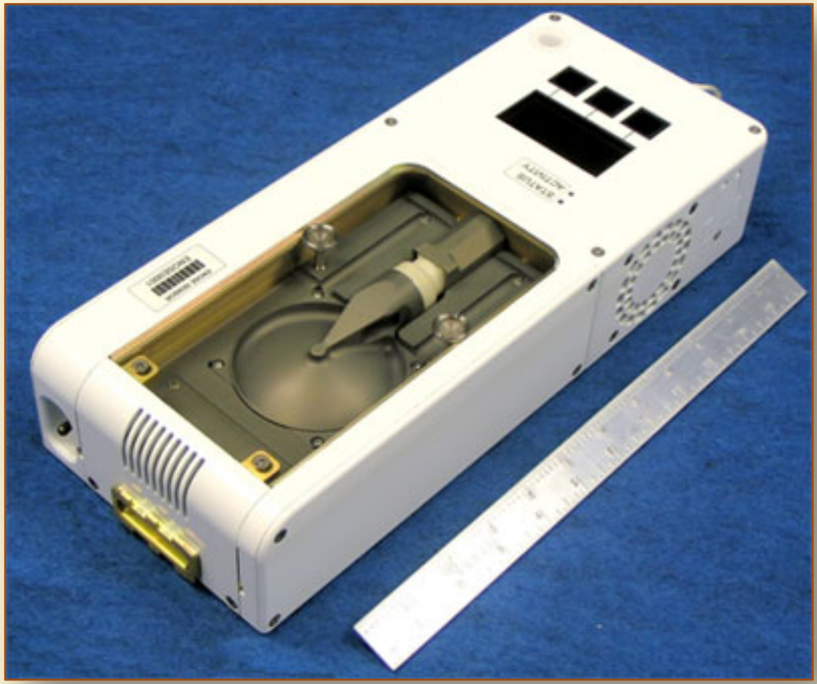
Lab-on-a-chip – Blood Analysis Chemical Sensor Array

[Photo courtesy of Y. Tai, California Institute of Technology]

A miniaturized, portable blood-count device used by astronauts to analyze blood samples, in real-time, to diagnose infection, allergies, anemia or deficiencies in the immune system.

CSA as Olfactory Sensor (Enose)

- Artificial olfactory system or nose (Enose)
- Analyzes a fragrance by separating the particles that provide an overall scent.
- Used to detect specific compounds in a food's odor.
- Determine the freshness of the meat or the presence of contaminants.

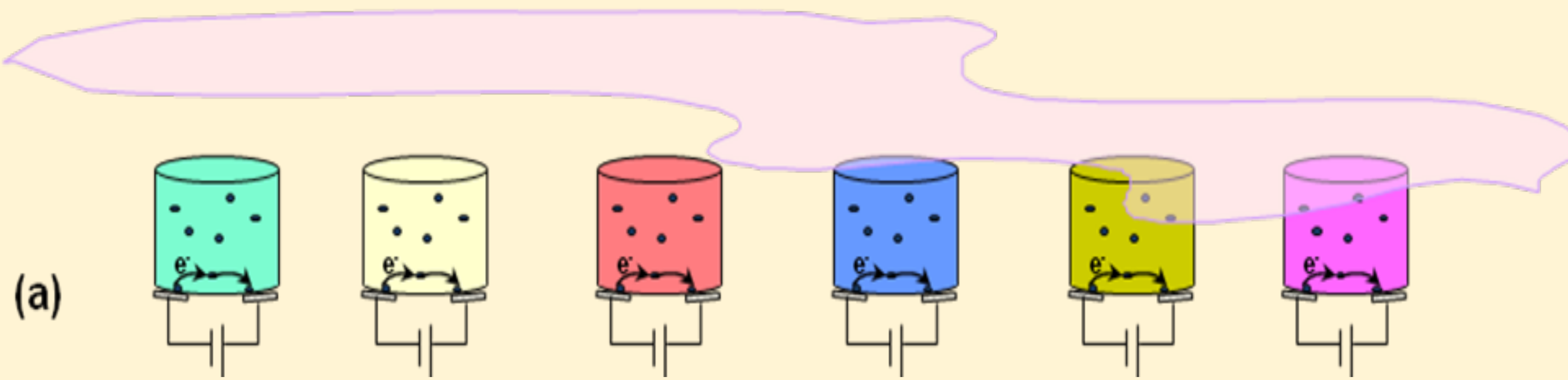


The picture is the ENose developed by NASA and tested on the International Space Station in late 2008. The ENose Sensor Unit (the darker-looking metal object) is housed in its Interface Unit (white). It is currently used in the space station to detect ammonia.
[Graphic source: NASA]

How Does the ENose Work?

A collection of 16 different polymer films on a set of electrodes. *(The graphic (a) illustrates six films/electrodes.)*

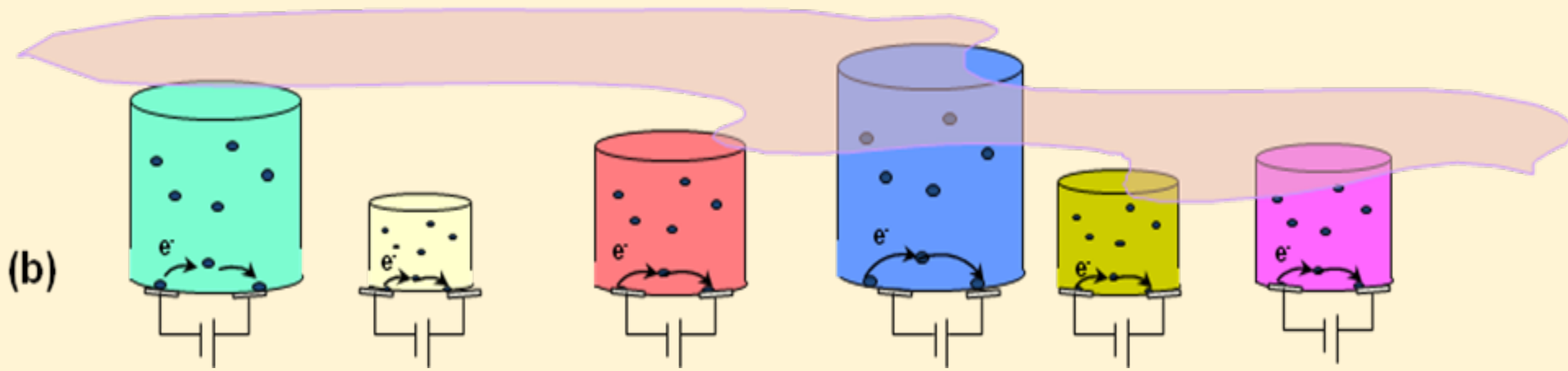
Films are specially designed to conduct electricity based on the film's resistance.



A baseline resistance reading is established with no odors (ambient air).

How Does the ENose Work?

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.



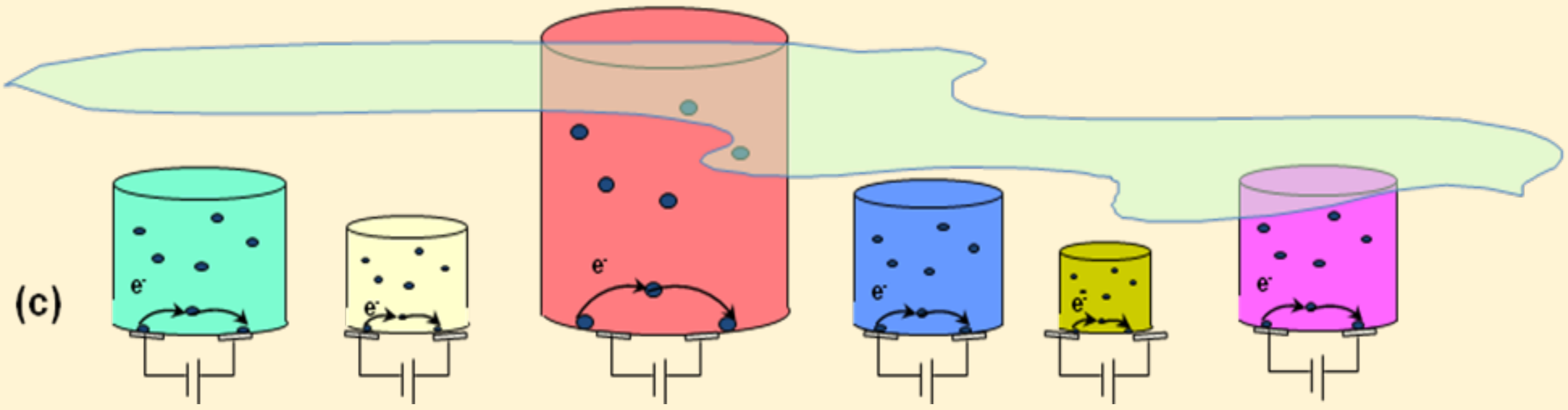
The amount of expansion of each film determines the amount of its electrode current.

How Does the ENose Work?

Each polymer reacts differently to a chemical compound.

Changes in resistivity in a single polymer film would not be enough to identify a compound; however, the cumulative changes of the 16 films produce a distinctive, identifiable pattern for a specific compound.

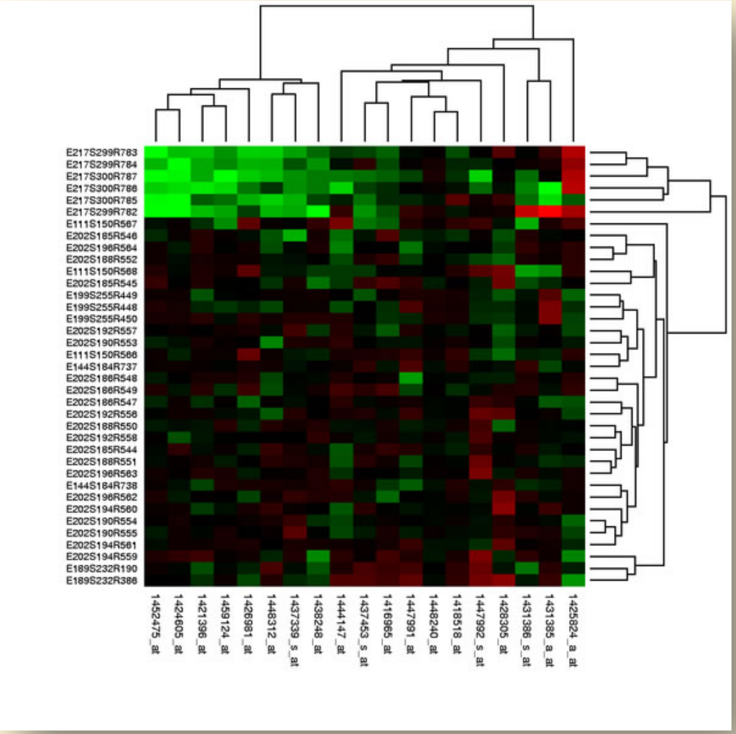
(c)



This graphic shows a different compound being sensed.

Biosensors

- Analyze samples for substances such as antibodies, proteins, antigens, and DNA.
- Glucose monitors
- pH sensors
- DNA or gene microarrays analyze and measure the activity of genes.



***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]

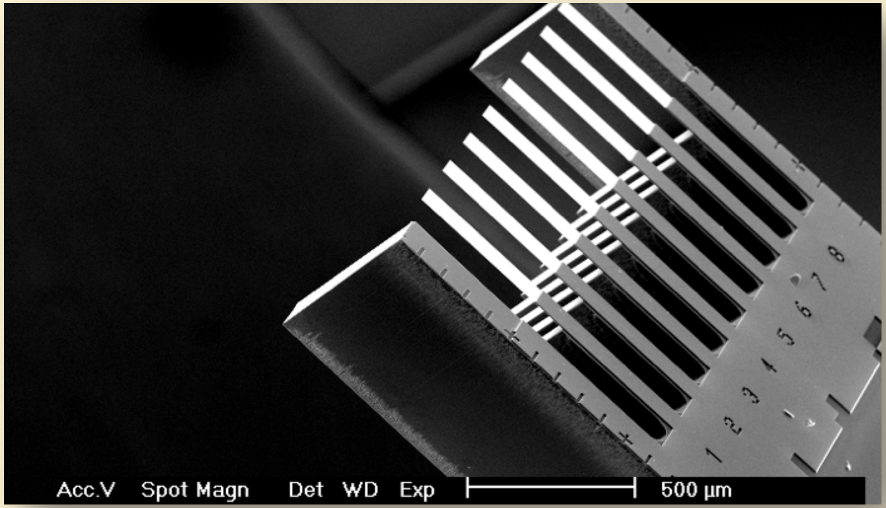
Challenging Environments

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

- Electric and magnetic fields
- Hazardous chemical vapors
- Nuclear radiation
- Radio frequency (RF) radiation
- Contaminated and hazardous liquids

Cantilever-Based Sensor Array

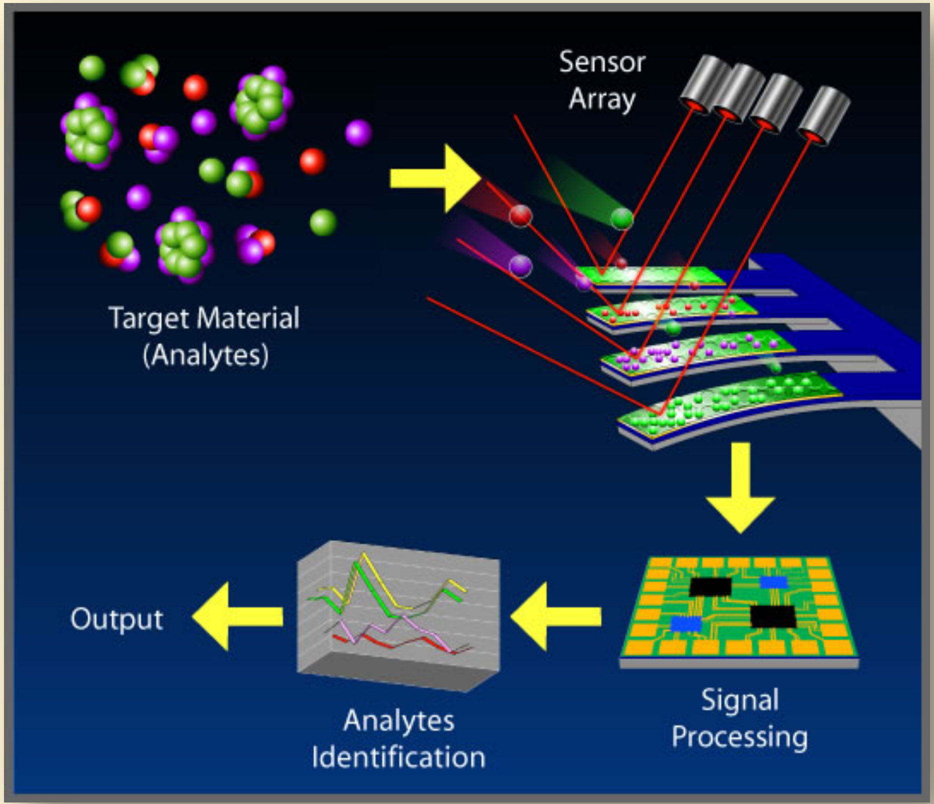
- The most common CSA transducer is the microcantilever.
- Its versatility and low construction costs make it an ideal transducer for a variety of analytes.
- Microcantilevers *(see SEM picture)* are typically 10 – 500 µm long, up to 100 µm wide, and up to 2 µm thick. A pitch of 250 mm is standard in optical-fiber array applications.



Scanning Electron Microscope (SEM) image of a Cantilever Sensor Array (These cantilevers were developed by the Swiss Nanoscience Institute for proteomic and genomic applications.

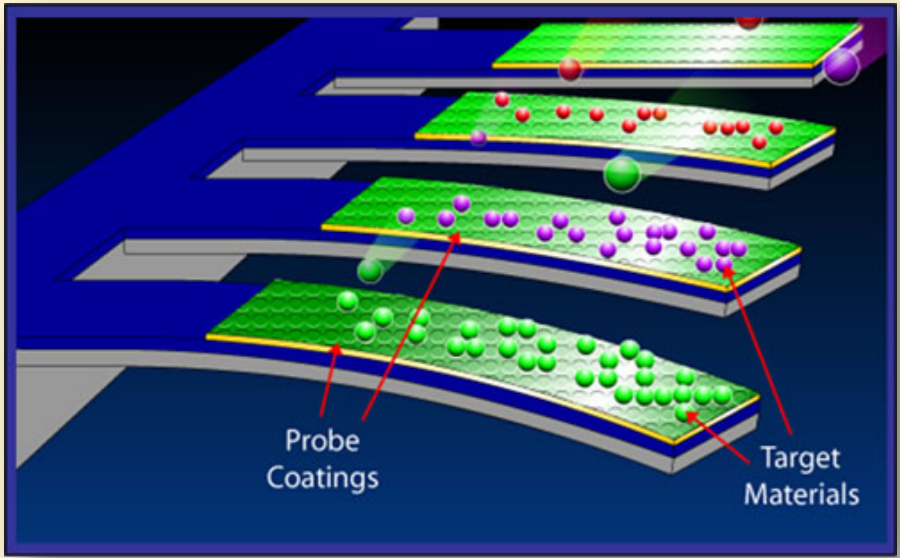
[Image courtesy of Dr. Christoph Gerber, Institute of Physics, University of Basel]

How does a Cantilever-Based CSA work?



The Microcantilever of a CSA

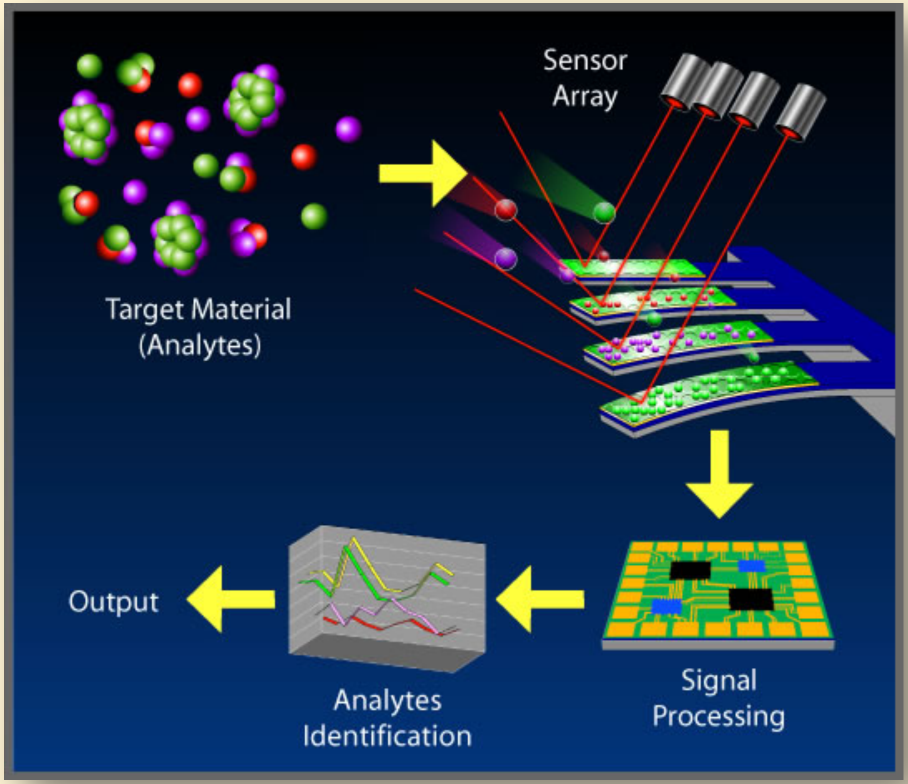
- Microcantilever transducers.
- Suspended end is coated with a chemically sensitive probe coating which experiences a chemical change when an analyte is adsorbed.
- Different probe coatings on each cantilever can allow for the detection of several different substances within the same sample.



In the above graphic, the probe coating is deposited on a gold layer. Each coating is designed to detect one and only one target material (analyte). The back microcantilever is the reference transducer.

CSA Block Diagram

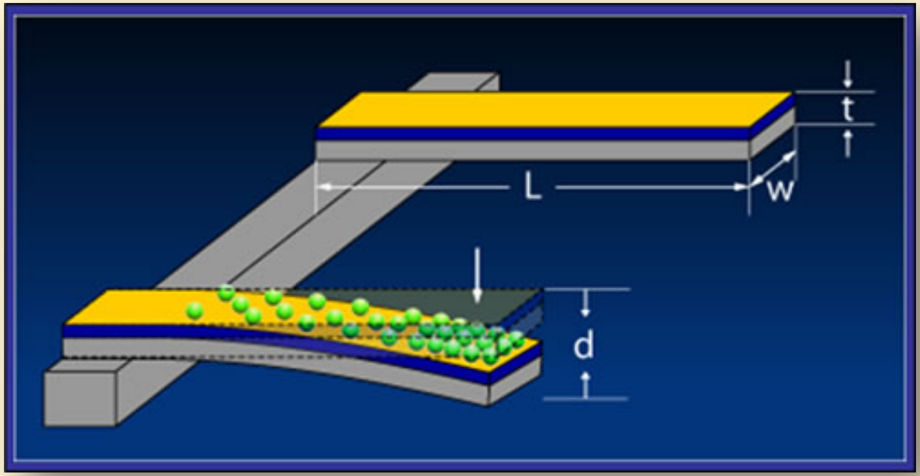
- Analyte binds to the probe coating causing a minute, but measurable change in the cantilever's mechanical or electrical properties.
- The change is measured and processed by the integrated circuitry *(Signal Processing)*.
- The data is analyzed and compared to reference data for determining the type and amount of analytes *(Analytes Identification)*.



An Interesting Fact

- Prior to the onset of micron and nano-technology, these minute changes in the mechanical properties of such small devices were considered negligible.
- Current technology provides innovative methods for measuring these negligible changes allowing microscopic components to be monitored and measured like their macroscopic equivalents.

Mass-Sensitive Transducers



Mass-Sensitive Transducer

- Microcantilever transducers have a sensitivity compared to similar macrotransducers.
- Overall mass is measurably affected by the chemisorption of a very small quantity or mass of material in the probe coating.
- A small change in mass causes a measurable change in one or more of the cantilever's properties.

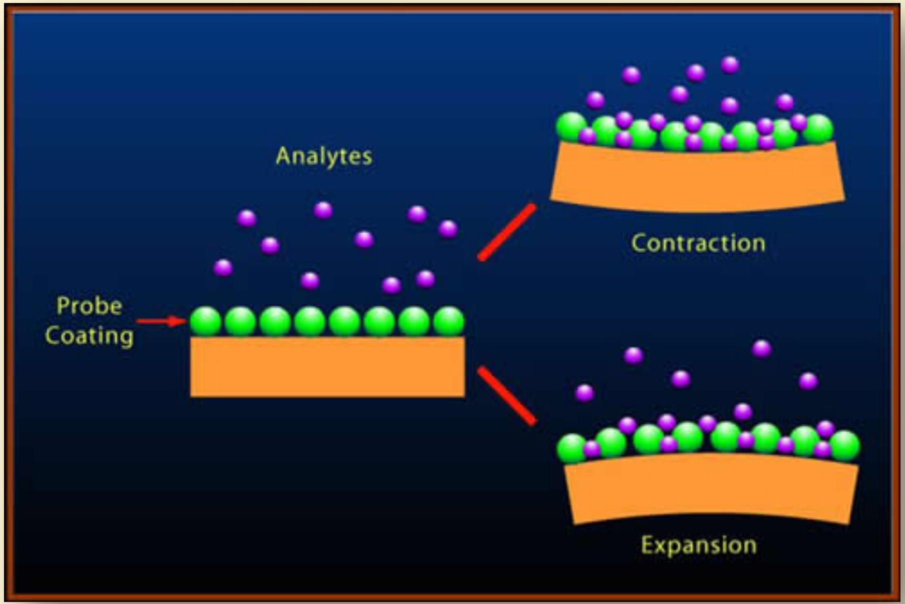
Stress-Induced Curvature

Mass-sensitive transducers become less effective as the transducer and analytes get smaller.

For nanosized analytes, cantilever displacement is caused by surface stress in the chemisorption of the analytes with the probe coating.

The adsorption the coating to expand or contract which *bends* the cantilever.

This is "stress-induced curvature."

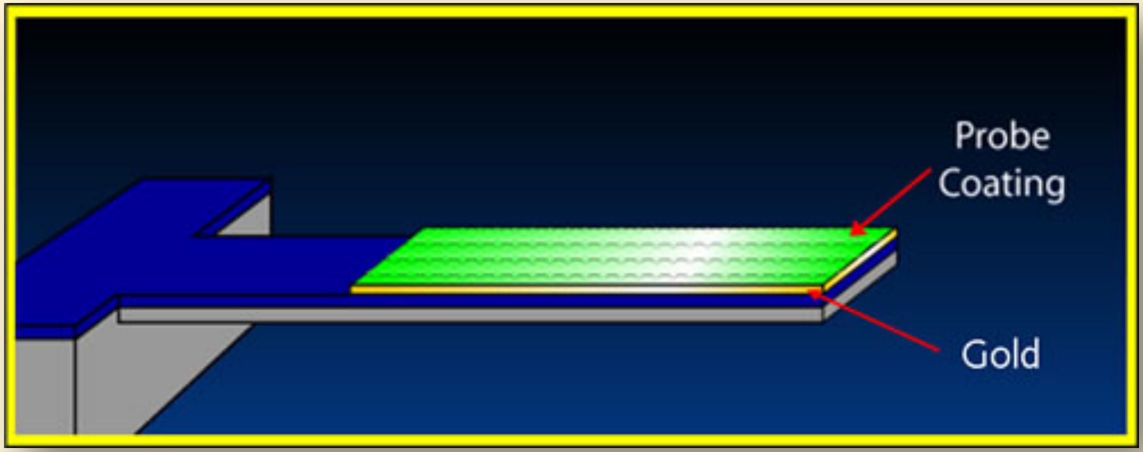


Static and Dynamic CSAs

Static and Dynamic modes of operation are used in CSAs.

- The **static mode** measures the bending of the cantilever.
- This bending is a static response, but it is measurable.
- The **dynamic mode** measures a shift in the cantilever's resonant frequency.

Cantilever Construction



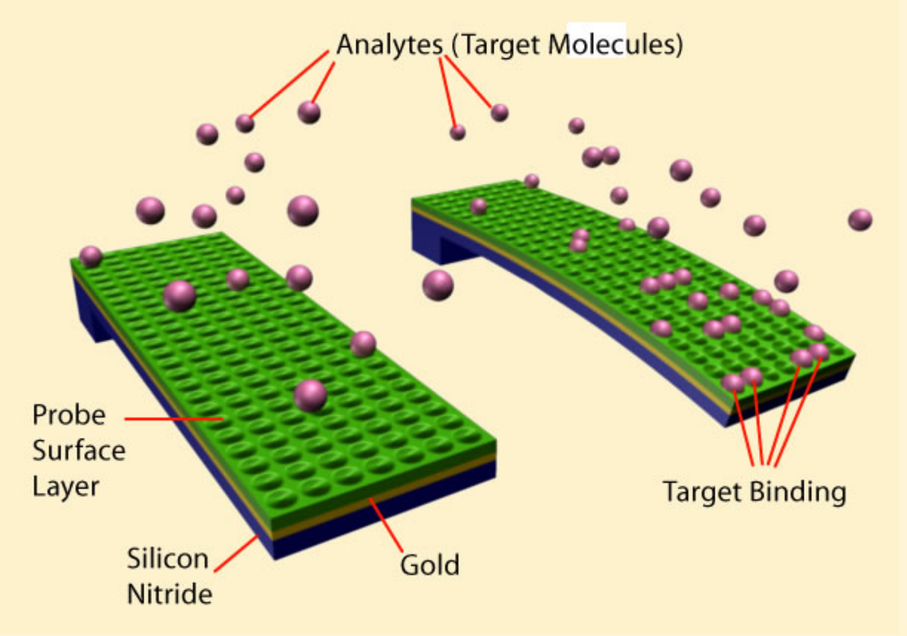
Functionalizing the Surface – Selecting coating a portion of the cantilever surface with the probe coating.

- For both the static and dynamic modes, the cantilevers are constructed with different surface coatings.
- The coating may cover only the tip of the suspended or the entire surface *(functionalizing the surface)*.
- Selective coating deposition process is referred to as "functionalizing the surface.

Static Mode

Functionalizing the Surface – Selecting coating a portion of the cantilever surface with the probe coating.

- As the chemically reactive surface selectively adsorbs the analytes, the cantilever bends due to surface stress.
- Bending causes a measurable cantilever displacement.
- Displacement is measured by sensing a change in angular deflection or resistance.

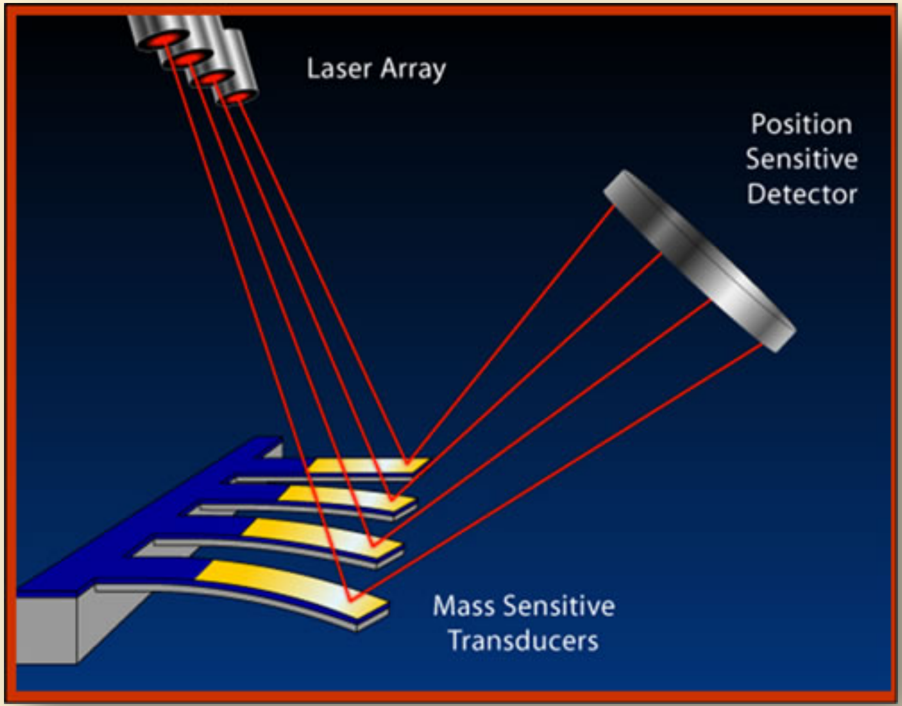


Static - Measuring ΔR (resistance)

- Piezoresistive material is fabricated into the microcantilever.
- As the target material is adsorbed by the chemically reactive layer the cantilever bends.
- This creates a measurable change in the resistance of the piezoresistive material.
- Amount of change is representative of the amount of analytes or their concentration within the sample.

Static – Measuring ΔAngular Deflection

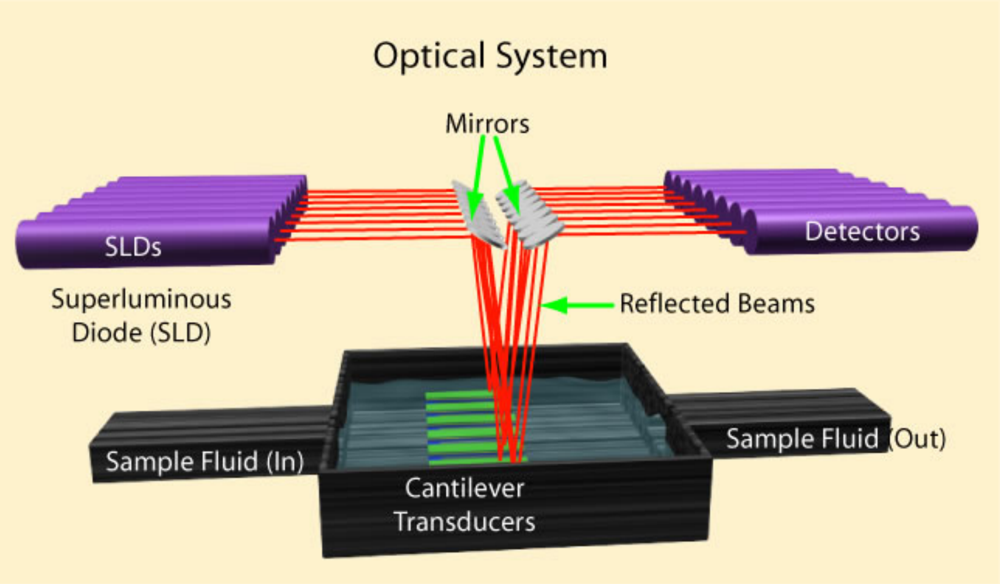
- A reflective layer is coated onto the surface of the microcantilever prior to the chemically reactive layer.
- A laser beam is reflected off the cantilever's surface creating a reference angle.
- As the cantilever bends, the change in the angular deflection is detected by measuring the change in position of the reflected beam.



Dynamic Mode

- Microcantilevers are initially excited by external actuation.
- Excitation results in an oscillation at resonant frequency.
- Analytes adsorb to the probe coating.
- Adsorption changes the cantilever's mass resulting in a change in resonant frequency.
- Amount of change in resonant frequency depends upon the concentration of the analytes and the amount of exposure time.

Static or Dynamic?



- In liquid environments the damping effect of the liquid on the cantilever's movement can result in false readings.
- Therefore, static CSA's are primarily used in liquid environments.
- Gaseous environments use both static and dynamic CSAs.

Operating Characteristics of CSAs

Operating characteristics include

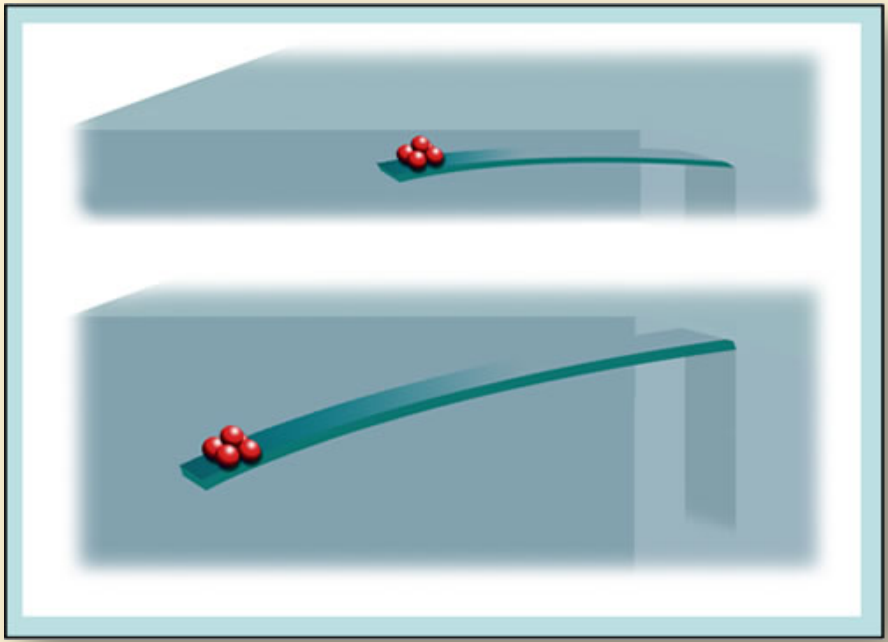
- Sensitivity
- Selectivity
- Response time
- Size
- Power consumption

Cantilever-based CSAs have proven to be

- highly sensitive,
- highly selective, and with
- fast response times.

Mass Sensitivity

- Microcantilever transducers have an inherently high mass sensitivity due to their small mass.
- The physical properties (width, thickness, length and material) are used to further enhance its sensitivity.
- Which cantilever would have a higher resonant frequency
  - short or long?
  - thick or thin?



Response Time

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.

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.

Other Types of CSAs

The type of CSA primarily discussed in this unit was a cantilever-based CSA that uses mass or stress sensitive transducers.

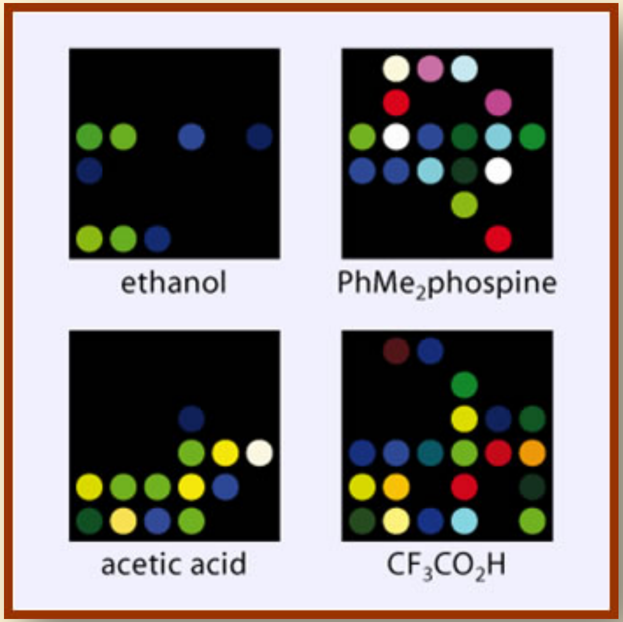
There are variations of CSAs that use other types of transducers that may be better suited for a specific application and its requirements.

Optical Sensor Arrays

A chemical reaction between the probe material and the analytes affects an optical property of the transducer such as color (wavelength) or light intensity.

The graphic shows a partial output from a colorimetric optical array which acts as an "optoelectronic nose“.

It uses an array of multiple dyes whose color changes are based on the full range of intermolecular interactions with the sample analytes and transducers.



The four volatile organic compounds in the graphic have four different patterns as identified by the sensor array.

Schottky Diode Sensor Array

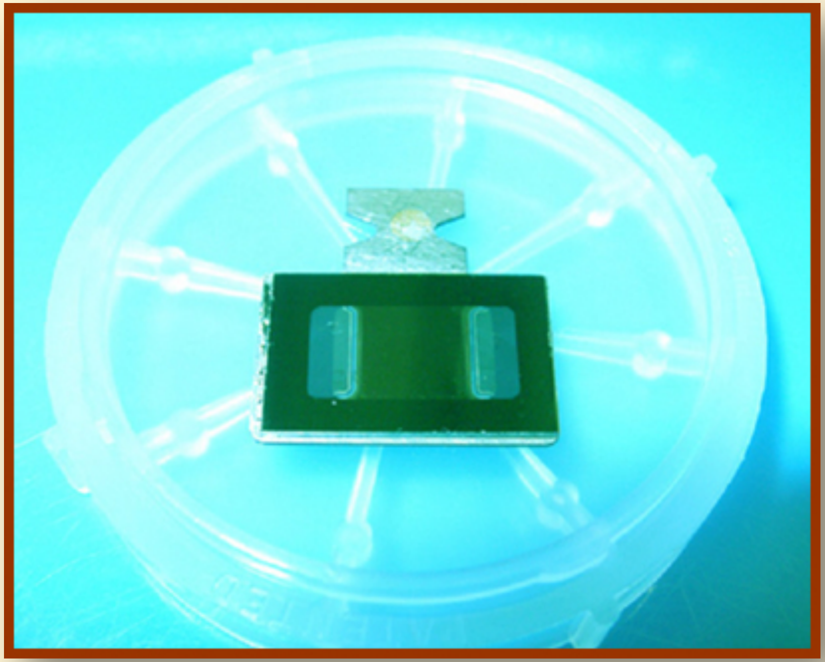
The target substance absorbs (diffuses) through the probe material to a metal layer.

The metal layer serves as the gate for a diode.

Any change at the gate causes a change in the diode's characteristics.

Here is a link to an animation on how a Schottky Diode Sensor works:

http://www.nsf.gov/od/lpa/news/press/01/pr01105flash.htm



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

Cell-based Sensor Arrays

- Cell-based Sensors use biological cells as the transducers to detect the presence of specific molecules within the cell's environment.
- One type of molecular transducer uses cell amplification.
- When a cell interacts with the analytes a chemical change occurs causing the production of many "so-called second messenger" molecules.
- This is a biological gain that can be measured to determine the amount of analytes in the sample.

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, and
- Acoustic arrays detect a change in acoustic properties as a result of interacting with the environment.

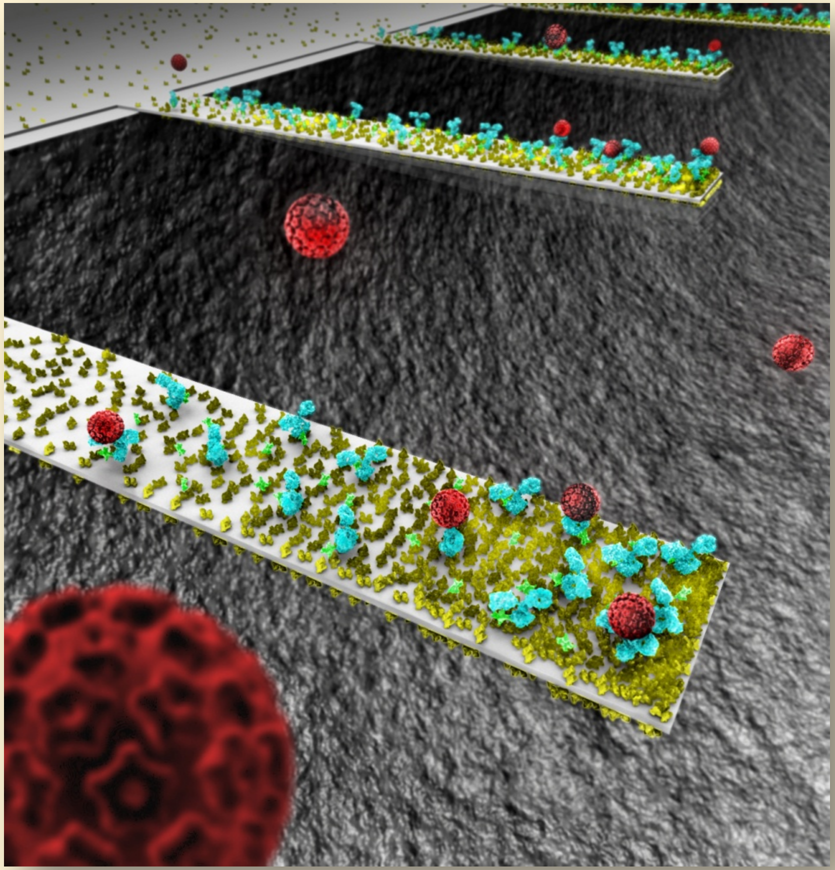
Food For Thought

- *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).*

Food For Thought

In many applications, dynamic mode or static mode CSAs could be used. This 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).*

Summary

- A cantilever-based CSA uses an array of microcantilevers to detect and measure specific materials within a sample environment.
- The micro 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.

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