Chap. 8 Micromechanical Systems

8.1 Introduction

- Microelectromechnical systems (MEMS) is the integration of mechanical components, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology.

8.2 Overview

- Control systems start with sensors. The microsensors can detect such properties as temperature, resistance, capacitance, chemical reactions, acoustic waves, and light.

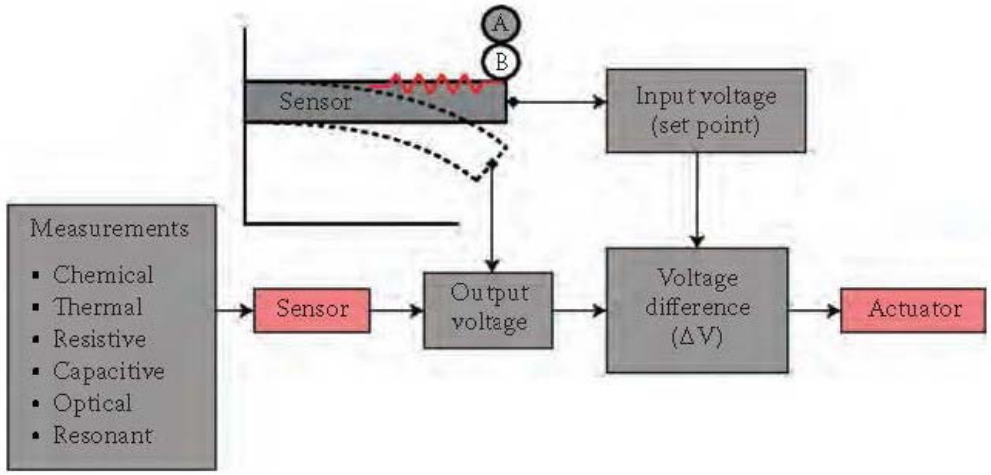

Figure 8.1 Illustration of a generic control system. The sensor measures the binding of analyte (A) to biomolecule (B), causing the cantilever beam to deflect downward. The beam deflection is compared to the set point voltage (without A). The voltage difference (ΔV) is measured, and the signal is sent to an actuator.

*Sensors and actuators are energy conversion devices (sometimes called 'transducers').
*Transducers transfer one type of energy into another type of energy, like converting mechanical energy into electrical energy and vice versa.

8.3 Microsensors

- Temperature Sensor
- Biosensor
- Pressure Sensor
- Resonating Mass Sensor: Magnetic Field-Induced, Laser-Induced
- Chemical Sensor
- Acoustic Wave Sensor

8.3.1 Temperature Sensor

- Thermocouples (TCs) are sensors that measure temperature of a heat source by converting it into voltage: thermoelectric effect that generates an electromotive force (voltage) at the ends of two dissimilar metal wires that are joined at a junction, T. Seebeck around 1820).

- Since 1980s, micro TCs have been directly fabricated as thin films on silicon chips.
  *The thermal sensors can be used on biochips to monitor the temperature cycles during a polymerase chain reaction (PCR) and the temperature of resistance heaters that vaporize analytes (samples that are analyzed).

- TCs consist of two dissimilar metal thin films (0.2 - 2 um thick) that are vacuum deposited onto various substrates.
  *Chromel (Ni-Cr alloy)/Alumel (Ni-Al alloy) and Fe/Constantan (Cu-Ni alloy) have been joined together at a junction to form a TC bead.

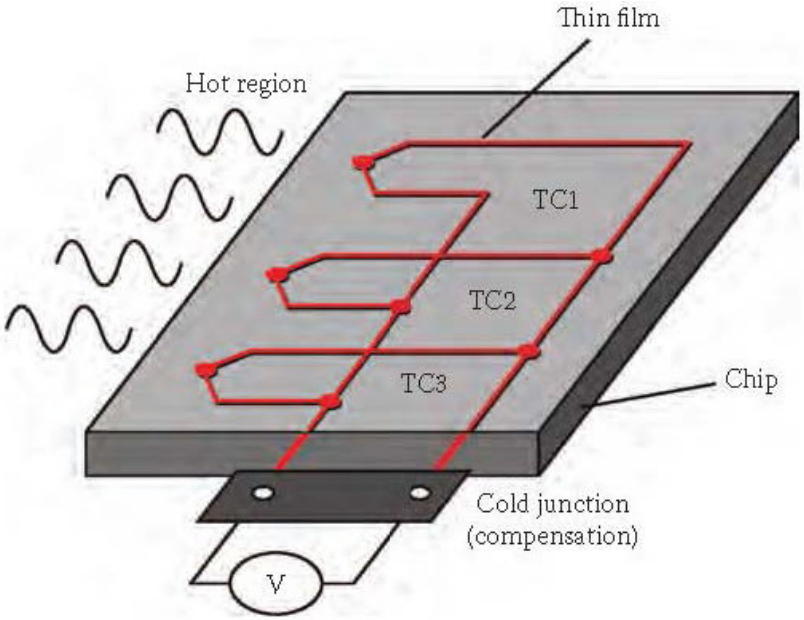

Figure 8.2 Schematic diagram of three thin-film TCs (TC1, TC2, TC3) deposited onto a substrate (chip). They are connected in parallel measuring the temperature at three different locations on a chip. [Adapted from Hsu, T.-R., *MEMS and*

*When the bead heats up, the TC generates a voltage, which has been calibrated with temperature.

8.3.2 Biosensor

- Many types of biosensors that can detect the presence of chemicals, nucleic acid molecules, and proteins: detection of the presence of 'A' which can be a protein from a diseased cell.
  *A way to sense the protein would be to select a suitable biomolecule 'B' or antibody that will bind to "A' - like a cancer protein that is attracted to an antiboby.

8.3.3 Pressure Sensor

- Monitoring of a person's blood pressure, intrauterine pressure, and bladder pressure.

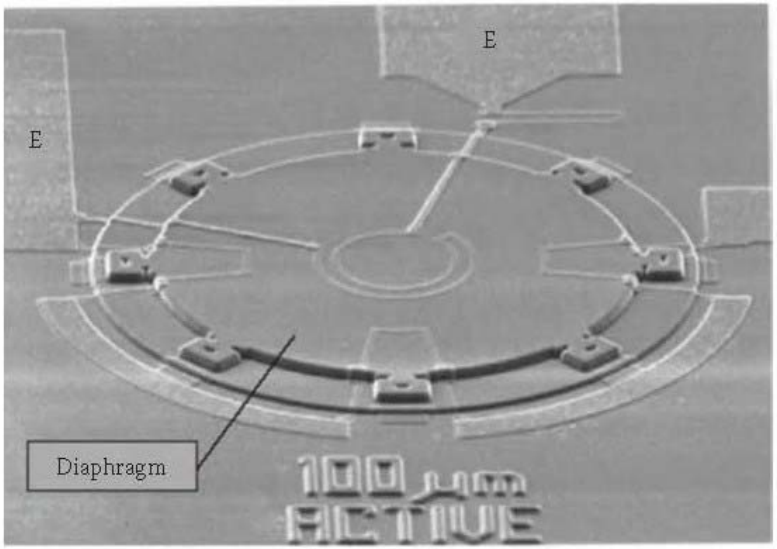

Figure 8.3 SEM image of an piezoresistive pressure sensor on top of a diaphragm. E = electrode.

*Capacitive pressure sensor

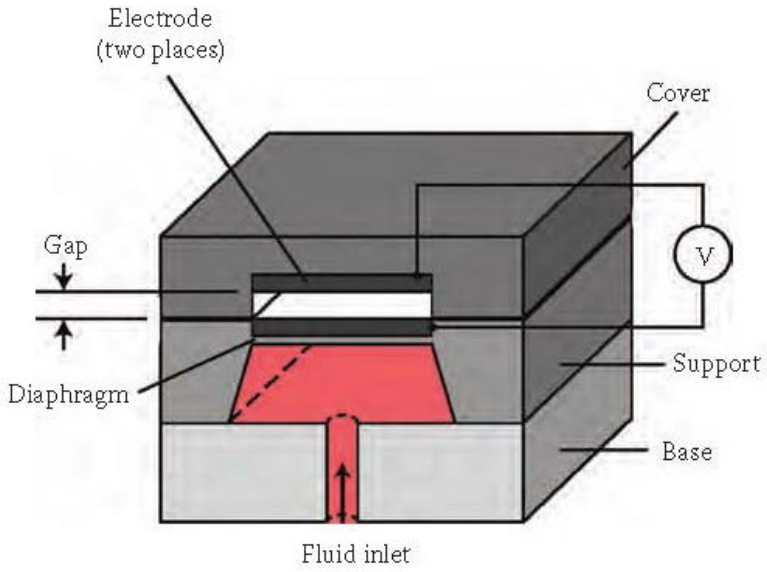

Figure 8.4 Three-dimensional cross-sectional illustration of capacitive pressure sensor and diaphragm with electrodes and cover attached. As fluid pressure is applied, the gap decreases and the voltage (V) is measured. [Adapted

8.3.4 Resonating Mass Sensor

- The principle of a vibrating a cantilever beam

- Mass sensor with high sensitivity on a chip in measuring molecules.
  1) Magnetic field-induced sensor
  2) Laser induced-sensor

1) Magnetic field-induced sensor (magnetic field is applied parallel to the *x*-axis)

- The frequency (f) of vibration: $f \sim (k/m)^{1/2}$ with mass *m* and the stiffness *k* of the beam

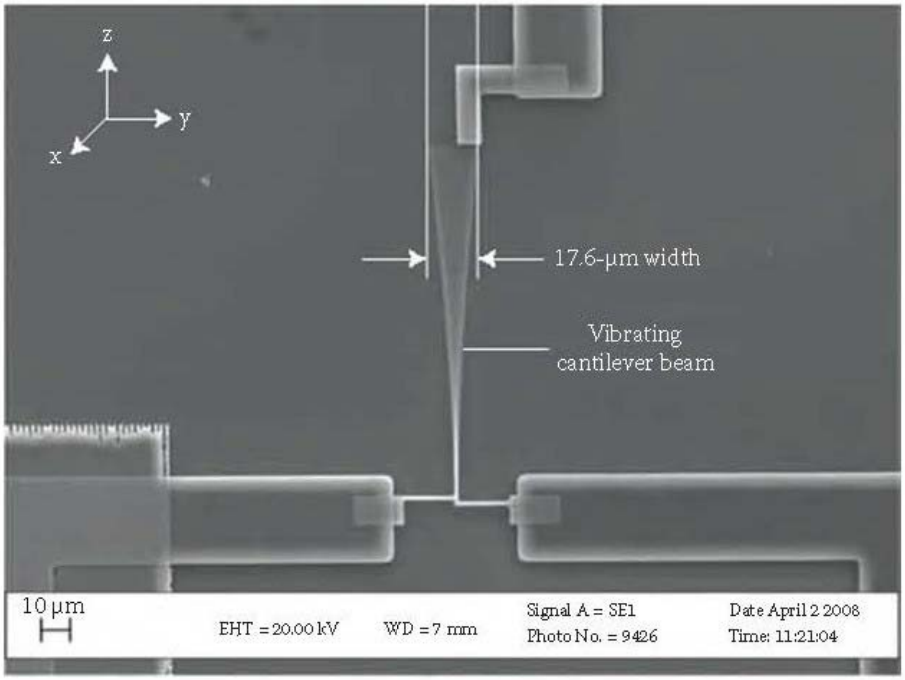

Figure 8.5 SEM image of a vertical cantilever beam that is vibrating. Beam vibration is along the y-axis.

2) Laser-induced sensor (IR laser beam in the y-axis to vibrate a cantilever beam)

8.3.5 Chemical Sensor

- Chemical sensors of pH, ions, gases, proteins, and glucose.
  *As semiconductors and transistors became widely used, the sensors became smaller and smaller.

1) Gas adsorption sensor: piezoelectric and field-effect transistor (FET)
   - Consist of a semiconductor tin oxide (SnO_2) piezoresistor that is deposited onto SiO_2.
   - SnO_2 sensors can detect a wide range of gases like H_2, CO, O_2, and H_2S: resistance change when foreign molecules are adsorbed.

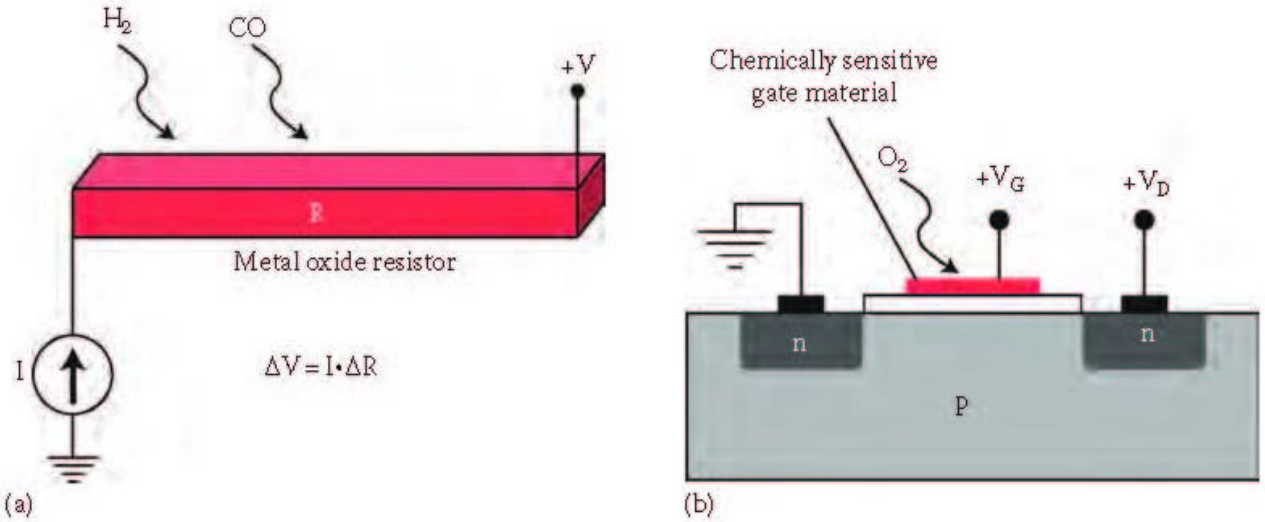

Figure 8.6 Schematic pictures of (a) piezo-resistance gas sensor (where R = resistance, I = current, V = voltage, and Δ = change). (b) FET gas sensor, where V_G = gate voltage, V_D = drain voltage. [Courtesy of Sandia National Laboratories,

2) Gas chromatography sensor

- Chromatography is a chemical method of separating and analyzing several molecules according to their size and mobility: vertical columns and spiral channels onto a MEMS chip.
  *The molecules are detected by their residence time in the channels (the smaller molecules diffuse faster through the channel than larger molecules).

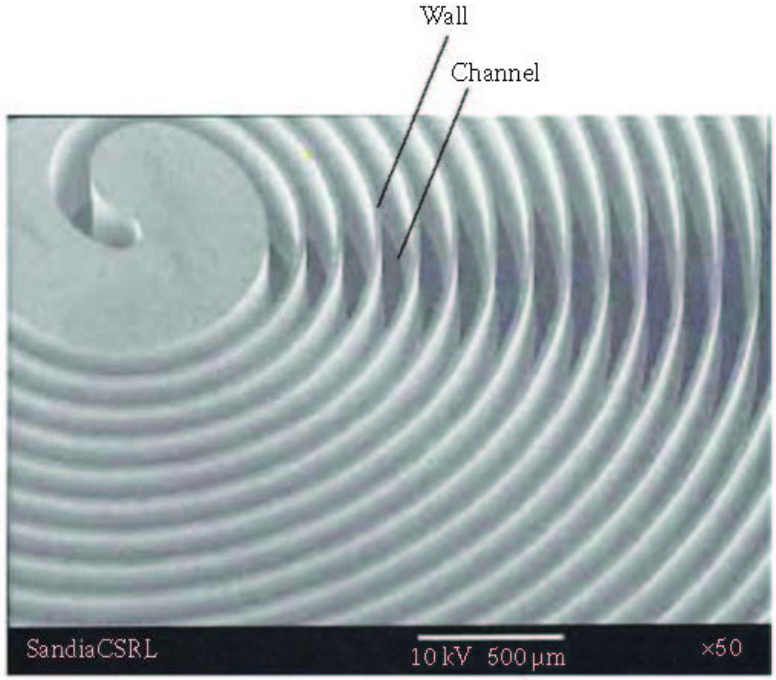

Figure 8.7 SEM image of spiral gas chromatograph column (top view) etched onto a silicon chip.

*The lower molecular mass is correlated with the shorter residence time.

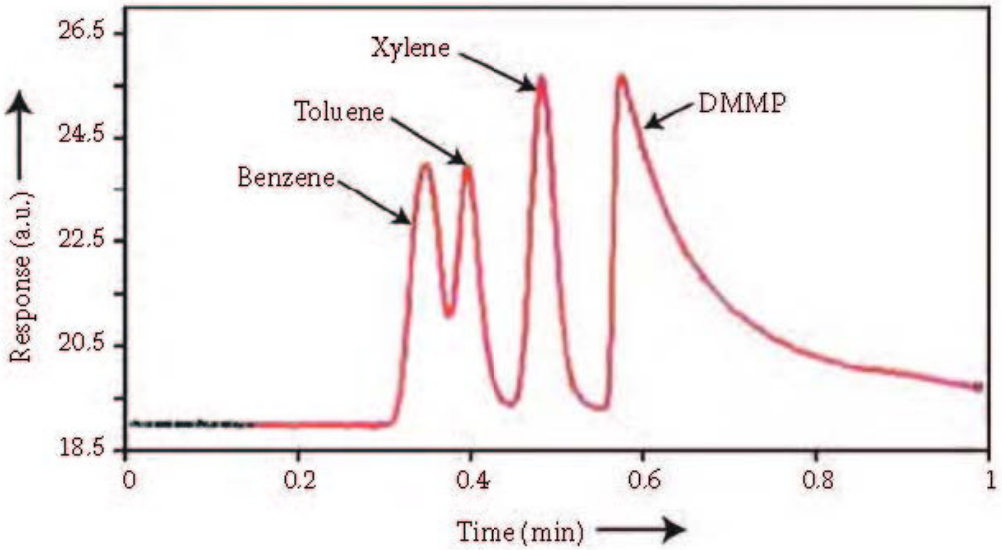

Figure 8.8 Data on the response vs. residence time of various gases diffusing through the spiraled column in Figure 8.7. DMMP = dimethyl methylphosphonate. [Courtesy of Sandia National Laboratories, Albuquerque, NM.]

8.3.6 Acoustic Wave Sensor

- Acoustic or sound waves can travel along the surface of a material (Rayleigh waves).
- The surface acoustic wave (SAW) sensors consist of capacitors and a SAW piezoelectric crystal, that act as transducers.

- Capacitors are designed to act as input and output transducers. SAW sensors convert electric energy into mechanical energy at the input transducer, which is then converted into acoustic energy and transferred to the output transducer, where it is converted back into electric energy.

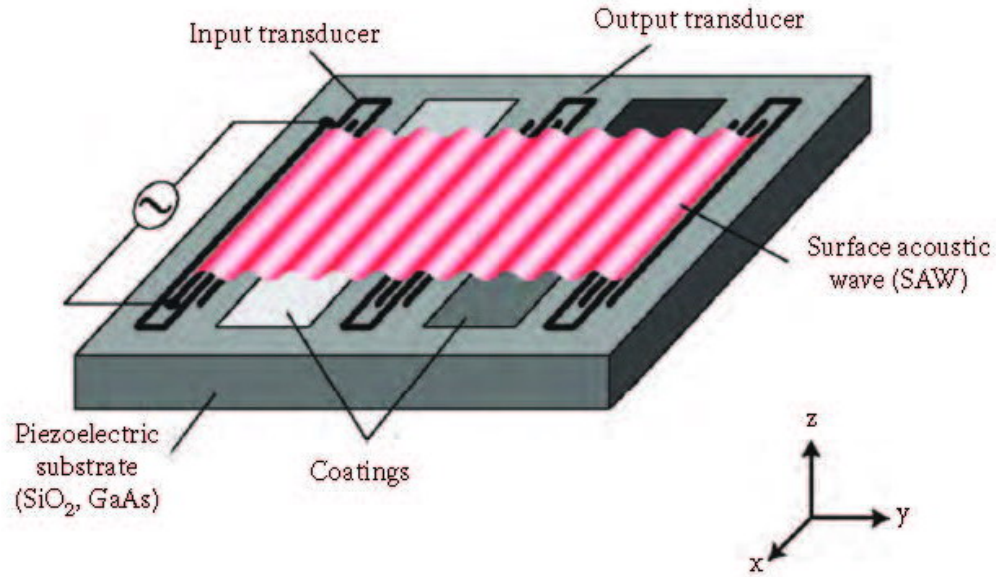

Figure 8.9 Schematic of SAW being generated by AC voltage on a piezoelectric substrate. Wave travels from the input transducer to the output transducer. [Courtesy of Sandia National Laboratories, Albuquerque, NM.]

- The velocity of a sound wave depends upon the medium that transmits the wave. Acoustic waves need molecules in the medium in order to be transmitted from the input transducer to the output transducer. The more molecules in the medium, the faster sound will travel.
  *Accordingly, the gas concentration can be determined from the wave transmission time.

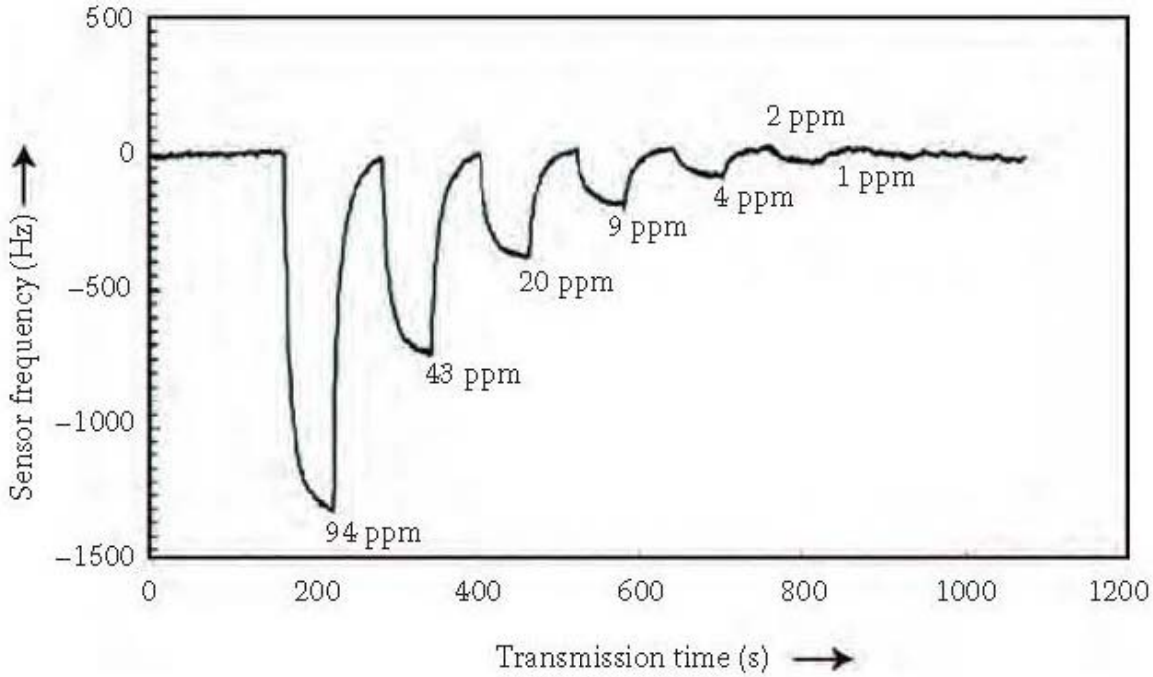

Figure 8.10 Data from SAW sensor on frequency vs. time response for flexural plate wave sensor in detecting xylene (Xe) at various concentrations, using an acoustic spectrum analyzer. [Courtesy of Sandia National Laboratories,

8.4 Microactuators (Reading assignment: p.354- p.362)

- Thermal actuator, cell manipulator, electrostatic motor, gear drive, piezoelectric cantilever beam, microelectric heater, microvalve, micropump

TABLE 8.1 Microactuators and Their Method of Actuation by Subsection

Number	Type of Actuator	Method of Actuation
8.4.1	Thermal actuator	Cantilever beam deflection
8.4.2	Cell manipulator	Gripping and manipulating cells
8.4.3	Electrostatic motor	Low pressure (vacuum) pumping
8.4.4	Gear drive	Turning valve "on-off"
8.4.5	Piezoelectric cantilever beam	Generating voltage
8.4.6	Microelectric heater	Vaporizing an analyte
8.4.7	Microvalve	Fluid flow control
8.4.8	Micropump	High pressure pumping

8.5 Biochips

- Defined as substrates (chips) that are fabricated using microminiaturization from the semiconductor industry for analyzing biochemical processes: the base material of the system can be either silicon, glass, or plastic.

- Microarrays vs. Microfluidics
- Microfluidic Devices

8.5.1 Microarrays vs. Microfluidics (see Figs. 2.37-2.41 in p.82 - p.86)

- Microarrays are simply color sensors - an array of circular spots on a chip.

- Microfluidics are sensors and actuators that control and manipulate the flow of fluids on a chip. *They include such devices as microchannels, mixers, pumps, valves, filters, and analyzers.

- Both microarrays and microfluidic systems can be used in biomedical applications such as DNA sequencing, identifying genes that cause specific diseases, and screening drugs for therapeutic studies.

- Disadvantages of microarrays: slow chemical reaction, large consumption of sample material, low sensitivity of the analysis (the leakage of the probe chemicals).

- Benefits and shortcomings of microfluidics

  1) Benefits: using small volumes of fluid, requiring low energy (power) input, easy manufacturability and low cost, being disposable (one-time usage), having fast analysis time, conducting an integrated analysis with many processing steps.

  2) Shortcomings: immature technology (not fully developed), chemical and physical interactions with surfaces not completely controlled, small sampling of molecules (leading to possible error).

8.5.2 Microfluidic Devices

- Mifluidics has also been called 'lab-on-a-chip' and 'micro-total analysis system' (u-TAS).

- Able to to perform multiple processes on a chip: microchannels, lab-on-a-chip, integrated DNA analysis, nanopore-on-a-chip, microchemical analysis, micropost filters, and microfluidics in a pill.

  1) Microchannels

  - Microchannels guide the flow of fluids through the system, ranging in size from 10 to 100 nm.
  *When the size of the channel decreases, its surface area-to-volume ratio increases; therefore, the channel surfaces tend to be negatively charged and the fluid molecules adhere to the surfaces, making it more difficult for fluid to flow in a channel.

  - Different shaped-channels – rectangular, circular, and triangular.
  *The pressure drop per unit length ΔP is inversely proportional to D^2 with the diameter D.

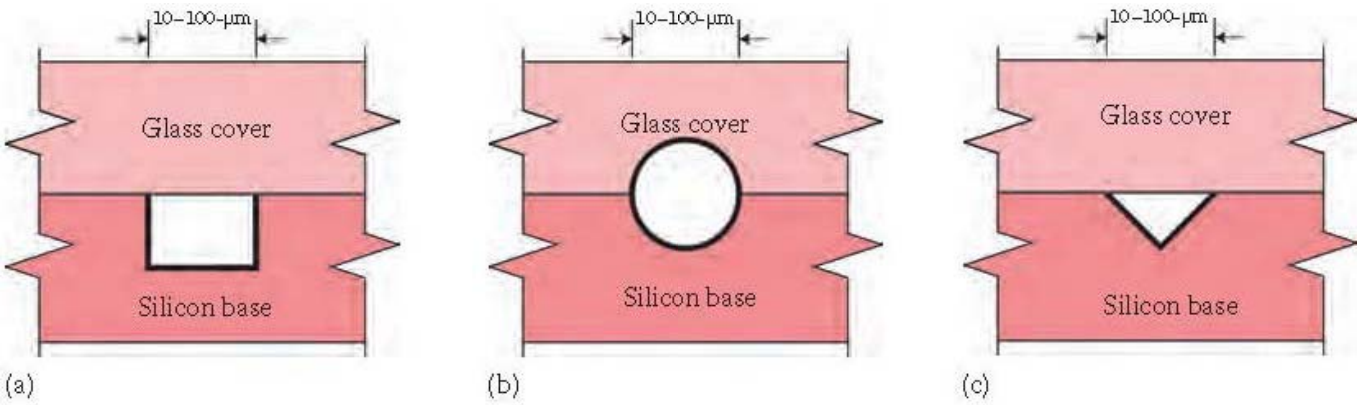

Figure 8.20 Cross-sectional illustrations of three different-shaped microchannels: (a) rectangular, (b) circular, and (c) triangular. Microchannels are in the silicon base that is bonded to glass covers. [Adapted from Hsu, T.-R., *MEMS and*

2) Lab-on-a-chip

- Analyze effectively the binding of a drug to diseased cells (commonly called 'drug efficacy').

- A prime solution is fed through the ports and suction (or vacuum) is applied to eliminate bubbles in the channel. A solution of diseased cells, drug, and fluorescent dye is added to the system. Then, a buffer fluid is added and mixed with the solution of cells, drug, and dye.

- When the drug binds to the diseased cells, the dye is released, and a laser beam excites the dye to fluorescent light. When this happens, the drug is effective in treating the diseased cells.

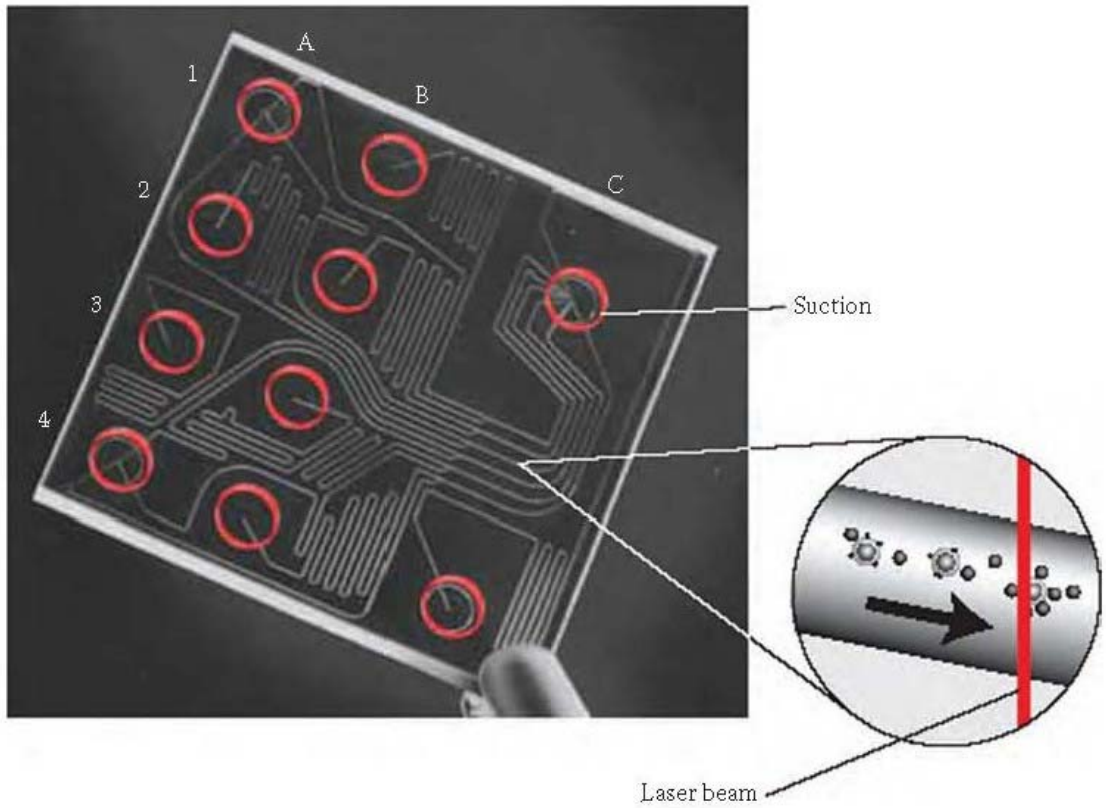

Figure 8.22 Photograph of Agilent's 2100 bioanalyzer system: microfluidic chip showing labeled ports, connected microchannels, and enlarged diagram of fluid flow (arrow) through a microchannel. Cells, drug molecules are shown in the enlarged view with laser beam. [Courtesy of Agilent Technologies Inc., Santa Clara, CA.]

*Reading assignment: p.368- p.373

3) Integrated DNA analysis, 4) Nanopore-on-a-chip, 5) Microchemical analysis
6) Micropost Filters,

7) Microfluidics in a Pill

- In 2008, a prototype iPill ('intelligent pill') at Philips Research: a microprocessor, battery, pH and temperature sensors, wireless radio transmitter, fluid pump, and drug dispenser.
  *The iPill is programmed to release the drug at the exact location of the disease (colitis, Crohn's disease, and colon cancer).

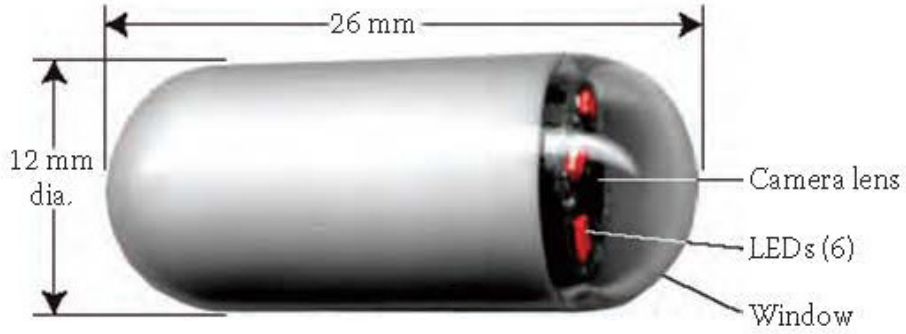

Figure 8.29 Photograph of a PillCam, an endoscopic capsule showing window, camera lens, and LEDs. There are actually six LEDs distributed around the camera. Only three are shown in red. [Courtesy of Euchiasmus/Images.]