Lectures on
MEMS and MICROSYSTEMS DESIGN
AND MANUFACTURE

Chapter 10

Microsystems Design

This chapter will synthesize the topics that were covered in all previous chapters into the electromechanical design of microsystems

MEMS and microsystems design differs from traditional engineering design is that in additional to the design for structural integrity and performance of the device or system, the designer's responsibility also include:

- Signal transduction
- Fabrication processes and manufacturing techniques
- Packaging
- Assembly
- Testing

Systems integration of microsystems and microelectronics is another major design task. It will not be covered in this chapter.

Topics in this chapter will include:

- Initial design considerations
- Fabrication process design
- Mechanical design, including using the finite element method
- Design of microfluidic network systems with a case study on electrophoresis systems design
- Computer-aided design in MEMS and microsystems

Three Major Interrelated Tasks in Microsystems Design

(1) Fabrication process flow design

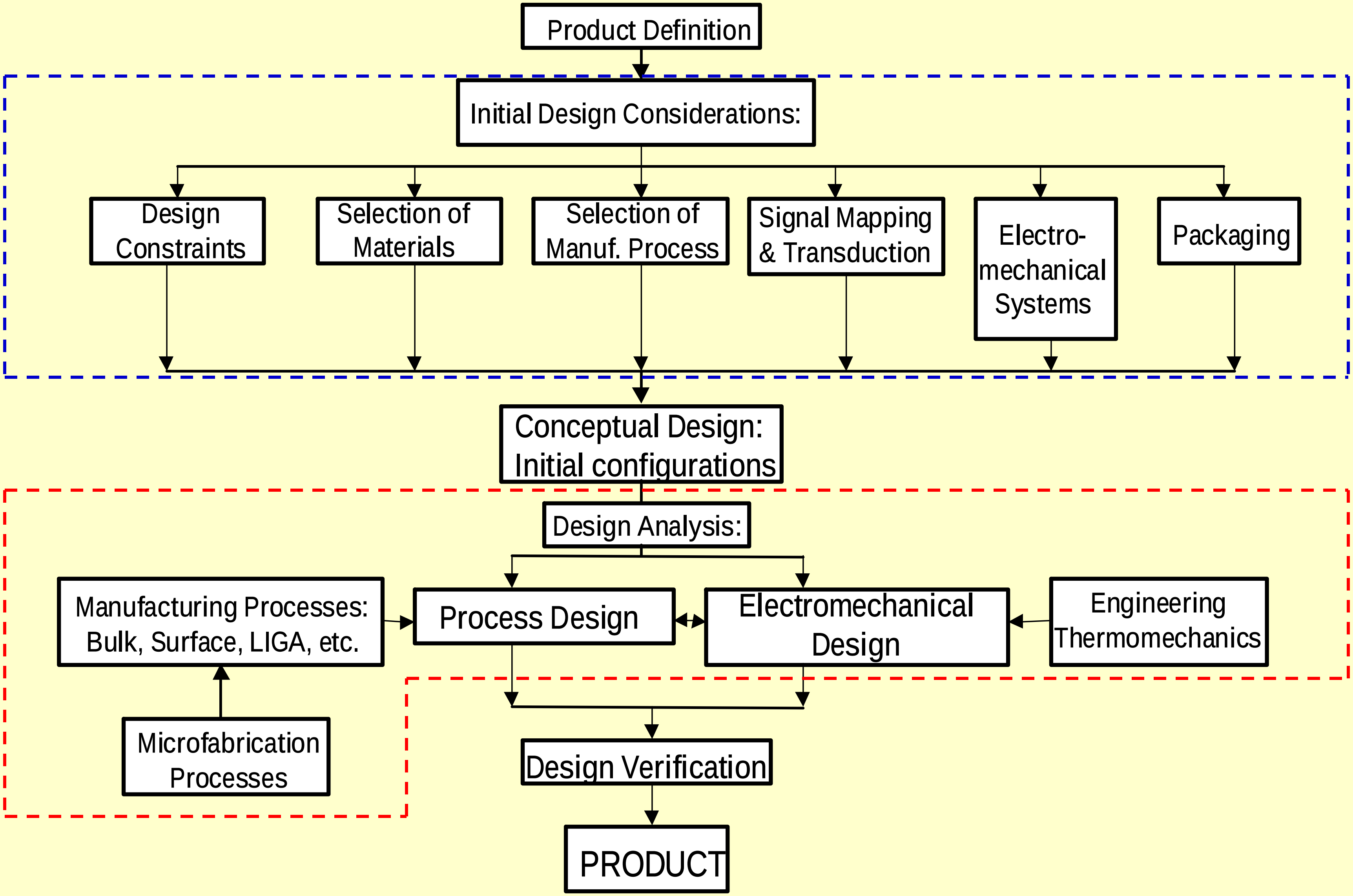
(2) Electromechanical and structural design

(3) Design verifications:

Assembly
Packaging
Testing

Microsystems Design

An overview of microsystems design:



Product Definition

Initial Design Considerations:

Design Constraints

Selection of Materials

Selection of Manuf. Process

Signal Mapping & Transduction

Electro-mechanical Systems

Packaging

Conceptual Design: Initial configurations

Design Analysis:

Manufacturing Processes: Bulk, Surface, LIGA, etc.

Process Design

Electromechanical Design

Engineering Thermomechanics

Microfabrication Processes

Design Verification

PRODUCT

Initial Design Considerations

- **Design constraints:**
  - Customer demands: applications; product specifications; operating environments
  - Time to market
  - Environmental conditions: temperature; humidity; chemical; optical.
  - Size and weight limitations
  - Life expectance
  - Availability of fabrication facility
  - Costs

- **Selection of materials:** For substrate, components and packaging materials.

  - Substrate: Silicon, GaAs, Quartz and polymers
  - Thermal/electric insulation: SiO_2
  - Doping materials: B, P and As
  - Mask materials: SiO_2, Si_3N_4, quartz
  - Packaging materials: Adhesive, eutectic solder alloys, wirebond, encapsulation
  - Photoresists for photolithography
  - Thin films depositions

Initial Design Considerations - Cont'd

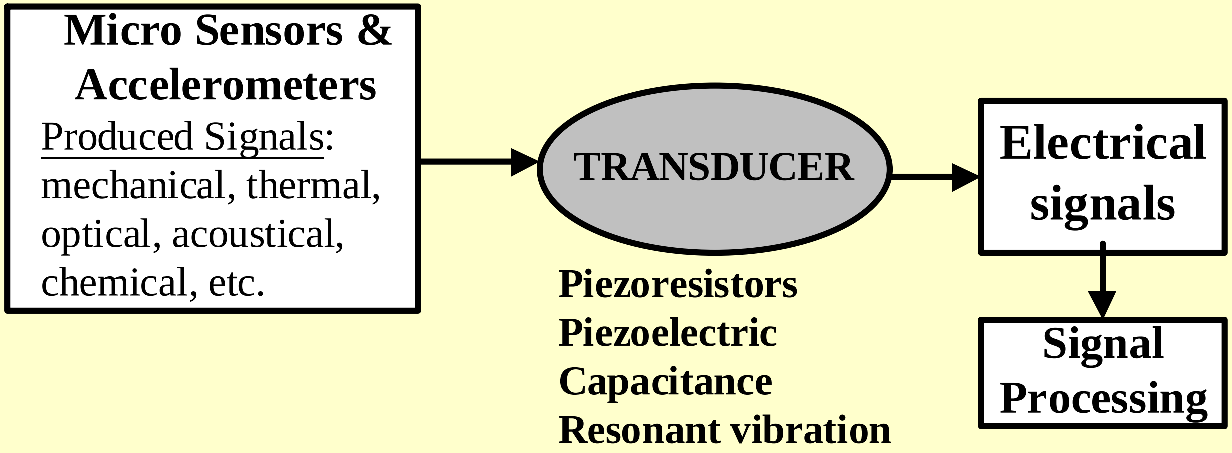
- **Selection of Manufacturing technique (s) and fabrication processes:**
  - **Micromanufacturing techniques:**

    Bulkmanufacturing; Surface micromachining; The LIGA process
- **Microfabrication processes:**

Processes	Principal applications	Building-up or building-in	High or low temperature	Approx. rate of production
Ion implantation (Sec. 8.3)	For doping p-n junctions or other impurities.	In	Low	Eq. (8.1)
Diffusion (Sec. 8.4)	For doping of p-n junctions of other impurities.	In	High	Eq. (8.4)
Oxidation (Sec. 8.5)	For SiO_2 layers using O_2 or steam.	In	High	Eqs. (8.9) and (8.10)
Deposition (Sec. 8.6)	Physical deposition for metals. Chemical deposition (APCVD, LPCVD, PECVD) for SiO_2, Si_3N_4 and polysilicons.	Up	Moderate to High	Eq. (8.23)
Sputtering (Sec. 8.7)	Thin metal films.	Up	High	P. 100, Madou Table 8.9
Epitaxy deposition (Sec. 8.8)	Thin films of the substrate material.	Up	High	
Electro-plating (Sec.10.3.2)	Thin metal films over polymer photo resist materials in LIGA process	UP	Low	Eq. (10.1)

Initial Design Considerations - Cont'd

- **Signal transduction:** **Types; Locations; Transduction methods; Inteconnects.**



Micro Sensors & Accelerometers

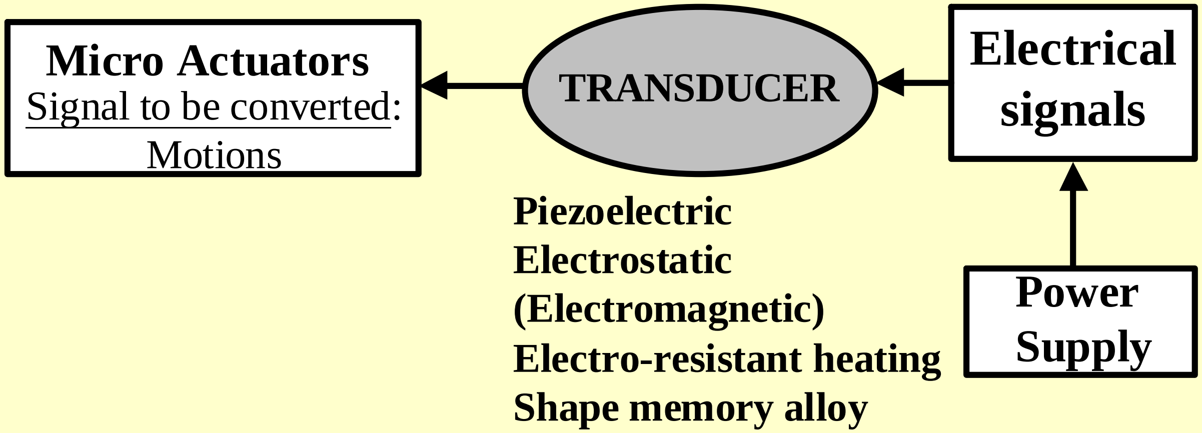
Produced Signals: mechanical, thermal, optical, acoustical, chemical, etc.

TRANSDUCER

Piezoresistors
Piezoelectric
Capacitance
Resonant vibration

Electrical signals

Signal Processing



Micro Actuators

Signal to be converted: Motions

TRANSDUCER

Piezoelectric
Electrostatic
(Electromagnetic)
Electro-resistant heating
Shape memory alloy

Electrical signals

Power Supply

Initial Design Considerations - Cont'd

- **Electromechanical systems:** Power supply; interface of MEMS/microsystems and microelectronics
- **Packaging:** **Materials, Process design Assembly strategy and methods, and Testing**
  - **Die passivation**
  - **Media protection**
  - **System protection**
  - **Electric interconnect**
  - **Electrical interface**
  - **Electromechanical isolation**
  - **Signal conditioning and processing**
  - **Mechanical joints (anodic bonding, TIG welding, adhesion, etc.)**
  - **Processes for tunneling and thin film lifting**
  - **Strategy and procedures for system assembly**
  - **Product reliability and performance testing**

Mechanical Design - Theoretical Bases

- Linear theory of elasticity for stress analysis
- Fourier law for heat conduction analysis
- Fick's law for diffusion analysis
- Navier-Stokes's equations for fluid dynamics analysis.

A "Rule-of-Thumb:

Mathematical models derived from these physical laws are valid for MEMS components > 1 μm

Mechanical Design – geometry

Common Geometry of MEMS Components

Beams:

Micro relays; gripping arms in a micro tong; beam spring in micro accelerometers

Plates:

Diaphragms in pressure sensors; plate-spring in micro accelerometers, etc.

Tubes:

Capillary tubes in micro fluidic network systems with electro-kinetic pumping
(e.g. electro-osmosis and electrophoresis)

Channels:

Closed and open-channels of rectangular and trapezoidal cross-sections
Channels of square, rectangular, trapezoidal cross-sections for microfluidic network

Unique geometry to MEMS and microsystems:

Multi-layers with thin films of dissimilar materials

Mechanical Design – Loading

1. Thermomechanical loading:

♦ Forces common to mechanical design:

- Concentrated forces in actuating micro beams and valves
- Distributed forces in pressure sensors diaphragms
- Dynamic or inertia forces in micro accelerometers
- Thermal forces due to temperature fields or mismatch of CTE
- Friction forces between moving and stationary parts in linear and rotary motors

♦ Forces unique in MEMS and microsystems design:

- Electrostatic forces for actuation in micro gripper arms, pressure sensor diaphragms and comb-drive resonators.
- Surface forces by piezoelectricity in micro pumping, e.g. inkjet printer heads
- van der Walls forces in closely spaced elements- a serious problem of “stiction” in surface micromachining and micro assembly

Mechanical Design – Analyses

2. Thermomechanical stress analysis:

- **Two principal methods:** close-formed solutions and finite element method

- **Intrinsic stresses/strains** inherent from microfabrication processes must be accounted for in the overall stress analysis

- Possible sources for intrinsic stresses:
  - Doping of impurities induces lattice mismatch and change of atomic sizes
  - Atomic peening due to ion bombardment
  - Micro voids in thin films created by the escape of carrier gases
  - Entrapment of carrier gases
  - Shrinkage of polymers during curing
  - Change of grain boundaries due to change of inter-atomic spacing after deposition of diffusion of foreign materials

- Realistic mechanistic models for intrinsic stress analysis need to be developed.

- Coupling of mechanical and electrical effects are common in MEMS design analysis, as encountered in the design of micro grippers and other actuators

Mechanical Design – Analyses

3. Dynamic analysis:

- **To determine the effect of inertia forces on MEMS and microsystems structures**
- **To assess the resonant vibration by modal analysis**
  - **Resonant vibration be avoided for most MEMS structures**
  - **Resonant vibration is desirable in some structures used as transduction to generate maximum signal output**
  - **Newton's second law relating to the equation of motion is used to assess the movement of MEMS structural components subject to vibration loading**
- **Stresses and strains induced by dynamic loading must be accounted for in the overall stress analysis of MEMS and microsystems**

4. Interfacial fracture mechanical analysis:

- This analysis is necessary whenever there are interfaces in MEMS or microsystem
- All surface micromachining processes will result in layered structures.
- Interfacial fracture mechanical analysis involves the use of the theories of linear elastic fracture mechanics
- All interfaces are subjected to coupled Mode I (opening) and Mode II (sliding or shear) fracture
- Finite element method is used to determine stresses in the materials on both sides of the interfaces
- Stress intensity factors of interfacing materials near the interface are determined by the established linear elastic fracture mechanics theory
- The determined stress intensity factors will indicate the stability of the interfaces under operating loads when they are compared with the experimentally determined fracture toughness

Simulation of Microfabrication Process Using FE Method

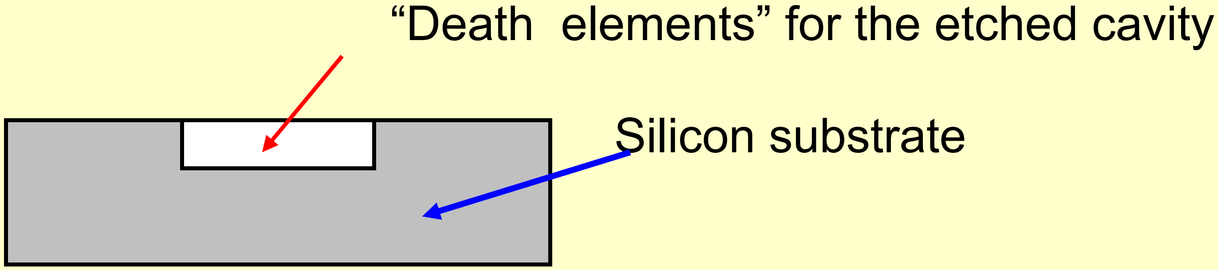
The essence of FEM is to discretize (divide) a structure made of continuum into a finite number of "elements" interconnected at "nodes." Elements are of specific geometry.

Two principal microfabrication processes for 3-D microstructures:

- **Type A: Adding materials to the substrate by deposition processes**
- **Type B: Removing material of the substrate by etching processes**

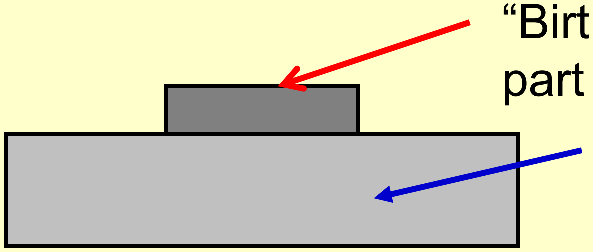
We may assign:

♦ **Parts of the structure created by Type B fabrication processes as the "DEATH" elements in the FE mesh for the finished structure geometry:**



Simulation of Microfabrication Process Using FE Method – Cont'd

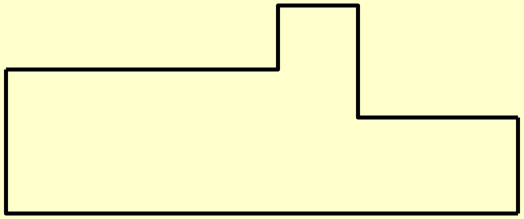
- ♦ **Parts of the structure created by Type A fabrication processes as the "BIRTH" elements in the FE mesh for the finished structure geometry:**



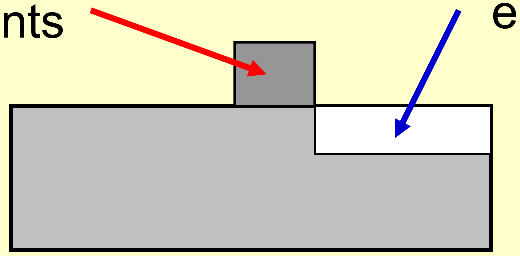
"Birth" elements for the added part of the structure.

Silicon substrate

- ♦ **There can be presence of both "Death" and "Birth" elements in the FE mesh of the overall structure.**



Profile of desired structural geometry



Part with "Birth" elements

Part with "Death" elements

Regions for FE mesh

Simulation of Microfabrication Process Using FE Method – Ends

- Both “Death” and “Birth” elements are originally included in the FE mesh of the “finished” overall structure of the microcomponent as “**pseudo-elements**” initially, with the following distinguished material properties:

- For **“Death” elements**: Initial properties are the same as the substrate material, e.g. switched to low Young’s modulus, E = 0+ and density ρ, but high yield strength, σ_y at the “end “of the predicted time for etching.

- For **“Birth” elements**: The assigned material properties, e.g. the Young’s modulus, density and yield strength are switched in the reverse order as in the case of “Death” elements at the “end” of the deposition process.

- Commercial FE packages, e.g. **ANSYS** and **ABACUS** have these special elements for simulating these specific microfabrication processes.

Design of Microfluidic Network Systems

- Fluids, especially liquids, require special pumping methods, e.g. electrokinetics to keep them flow in micro conduits (Chapter 5)

- **Microfluidic systems** involves: **micro valves**, **pumps** and **conduits of capillary tubes** or **open and close channels**

- Microfluidics are used in microfabrication processes, and more importantly, in biomedical applications in drug discovery and delivery, and diagnosis

- Two special microfluid flow techniques that are popular in **bioMEMS** are:
  - ♦ **Electro-osmosis**, and
  - ♦ **Electrophoresis**

  Working principles of electro-osmosis and electrophoresis were presented in Chapter 5

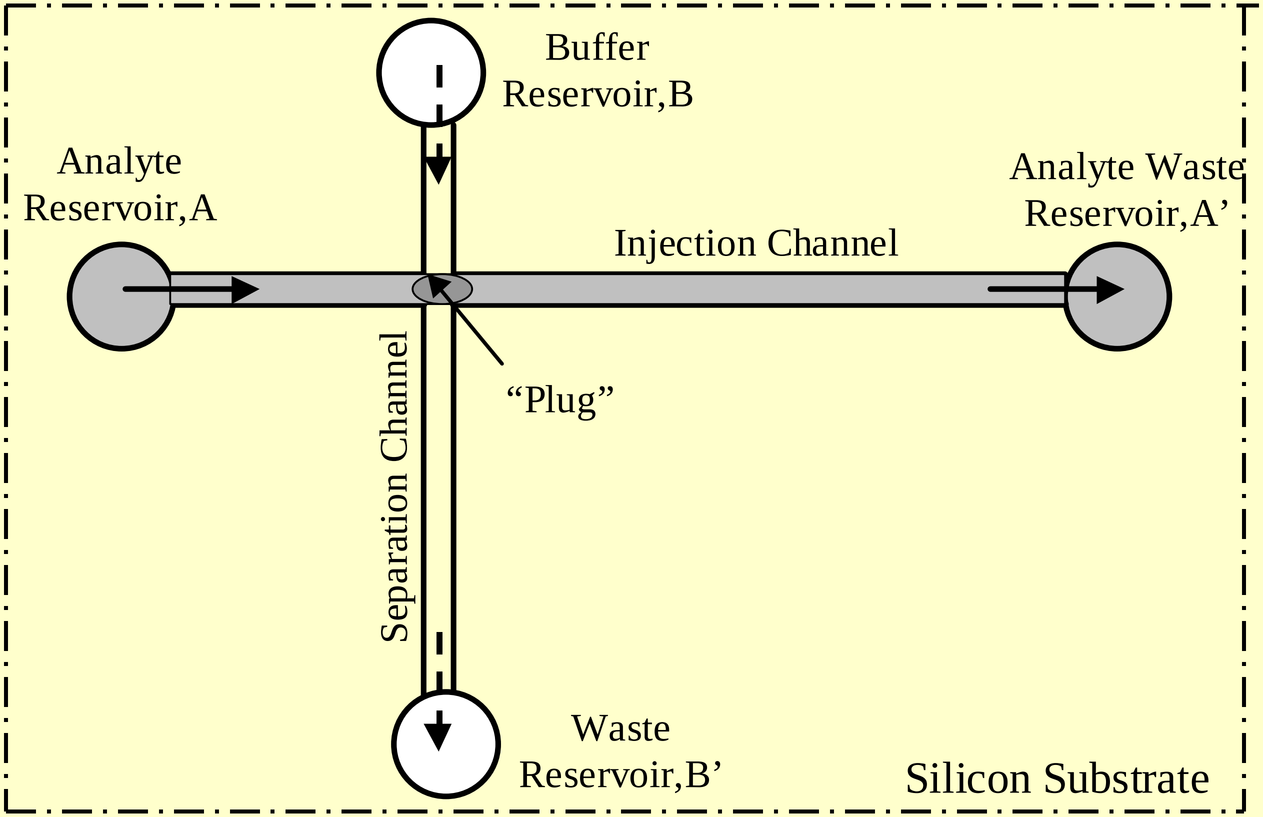
- Microfluidics involve the network of Capillary Electro-osmosis/Electrophoresis **(CE)** have been developed for biomedical analysis and medical diagnosis

- Capillary electrophoresis (CE) analyte systems are popular because: **Low-cost to produce, fast, accurate, small sample size and disposable** (cheap maintenance)

Design of Microfluidic Network Systems – Cont'd

Capillary electrophoresis (CE) network systems

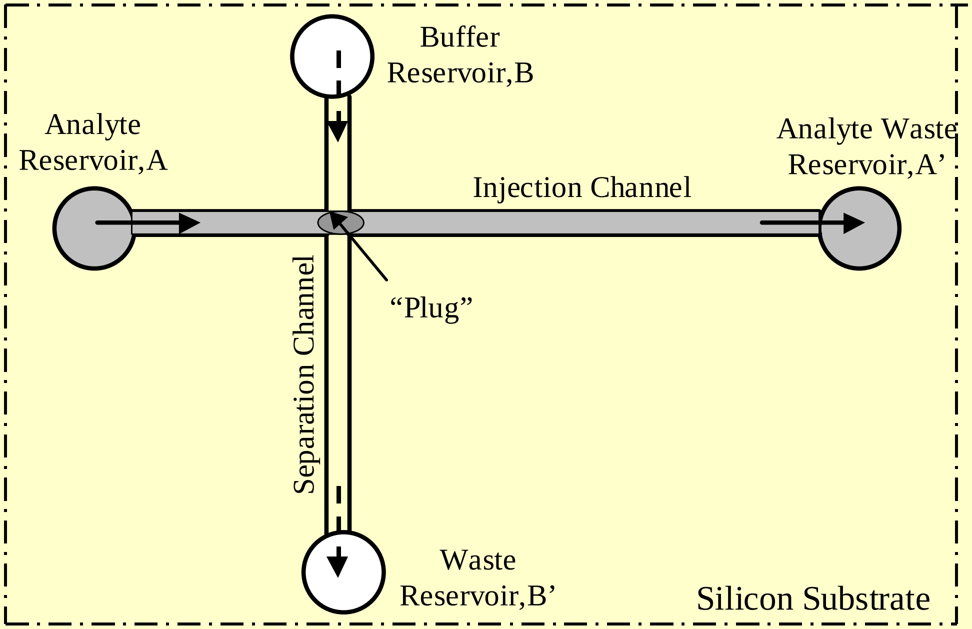
- The system involve at least two (2) capillary flow channels:
  - ♦ **Injection channel** for the passage of analyte solution that contain species to be identified
  - ♦ **Separation channel** for the passage of buffer solution that separate the species in the analyte solution for identification



Design of Microfluidic Network Systems – Cont'd

Working example on Capillary Electrophoresis (CE) network systems :

- Analyte solution is injected at Reservoir A.
- Apply 150 – 1500 V/cm between Reservoir A and A'
- The analyte solution will flow from A to A' by electro-osmosis
- A "plug" of the analyte solution is formed at the crossing of the two channels
- Electric field is then applied on the buffer solution between Reservoir B and B' with the flow in electro-phoresis



- The flowing buffer solution drives the "analyte plug" beyond the crossing of the two channels
- Various species in the analyte plug will separate due to the difference of "electro-osmostic mobility" of each individual species in the sample analyte
- Use amperometric electrochemical detector or fluorescence detector to identify the separated species in the sample after separation

Design of Microfluidic Network Systems – Cont’d

Mathematical modeling of capillary electrophoresis (CE) network systems

- Mathematical modeling of CE network systems operation is very complicated

- It involves the **coupling** of three (3) physical-chemical activities:

  - ♦ **Advection** (movement of a fluid involving temperature and material property changes),
  - ♦ **Diffusion**, and
  - ♦ **Electromigration**.

- Various **CFD** (Computational Fluid Dynamics) theories have been proposed to model this type of problems analytically.

- Commercial code “CFD-Ace$^+$” by CFD Research Corporation in Huntsville, Alabama is available to design and analyze this type of CE network systems.

Design of Microfluidic Network Systems – Cont'd

Mathematical modeling of capillary electrophoresis (CE) network systems -Cont'd

The advection equation:

$$\frac{\partial C_i}{\partial t} = -(\nabla \cdot \vec{J}_i) + \vec{r} \qquad (10.18)$$

in which C_i = concentration of species I in the solution

t = time into the process

$\vec{r}$ = the rate of production of the specie i (usually neglected)

The flux vector, $\vec{J}_i$ in the Eq. (10.18) has the form:

$$\vec{J}_i = \vec{V} C_i - z_i \omega_i C_i \nabla \phi - D_i \nabla C_i \qquad (10.19)$$

where $\vec{V}$ = Velocity vector of specie i in the solution, e.g. with components $V_x(x,y)$ and $V_y(x,y)$ in the respective x and y directions in a flow defined by the x-y plane

z_i = the valence of ion i

ω_i = **electro-osmotic mobility** of the ith specie = $\omega_i = \dfrac{z_i q}{6\pi r_i \mu}$

z_i = charge of ion i; r_i = radius of ion i; μ = dynamic viscosity of ion i

q = charge of an electron = 1.6022×10^{-19} Coulombs

ϕ = applied electrical potential

D_i = diffusion coefficient of the ith specie in the solution

Design of Microfluidic Network Systems – Cont'd

Mathematical modeling of capillary electrophoresis (CE) network systems -Ends

The **electric field equation** in Eq. (10.19) can be solved by using:

$$\nabla \cdot (\sigma \nabla \phi) = 0 \qquad (10.20)$$

in which the **electrical conductivity**, σ is defined as:

$$\sigma = F \sum_{i} z_i^2 \omega_i C_i \qquad (10.21)$$

where F = Faraday constant = 9.648 x 10^4 C/mol.

The **bulk fluid velocity** due to electro-osmotic mobility is:

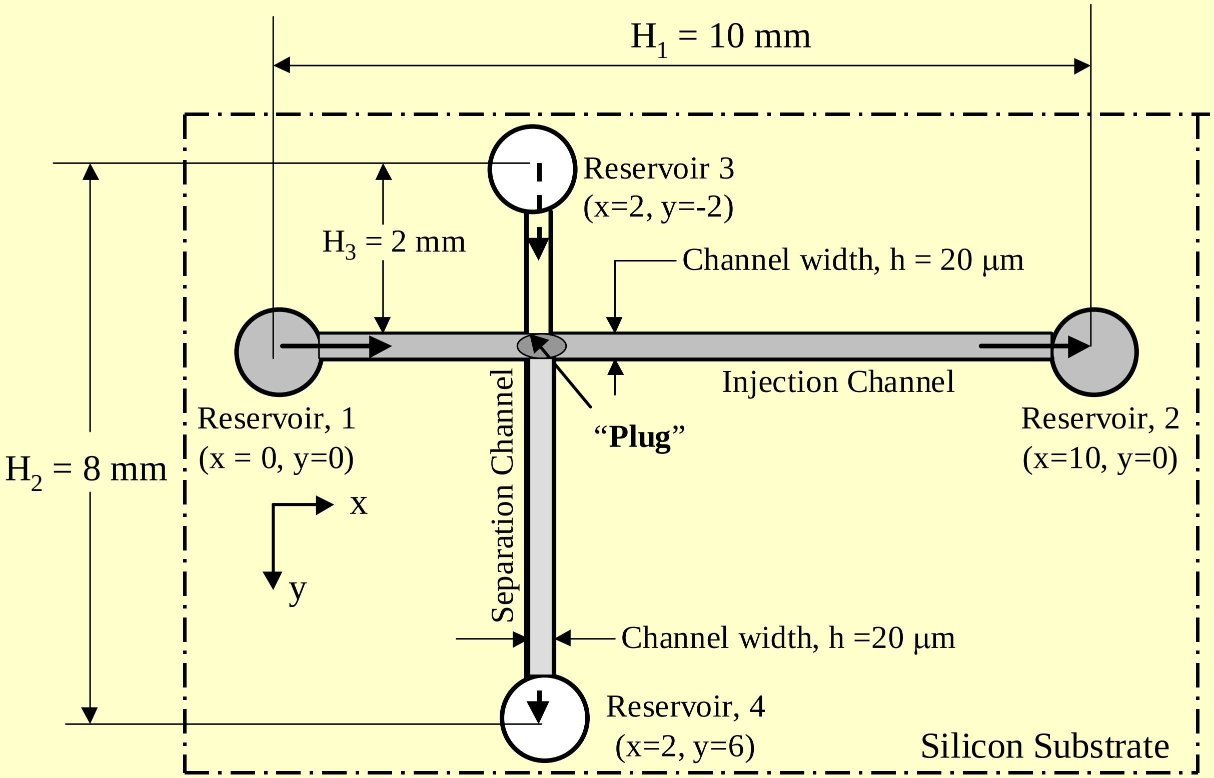
$$V_o = \omega_o \nabla \phi \qquad (10.22)$$

where V_o = imposed slip velocity at the channel wall
ω_o = electro-osmotic mobility of the species

Design of Microfluidic Network Systems – Cont'd

Design case: A CE network system

A numerical example of a CE process offered by S. Krishnamoorthy, CFD Research Corporation using CFD-Ace$^+$ code



- Rectangular channel:
  20 μm wide x 15 μm deep
- 3 species in the sample
- electro-osmotic mobilities of species:
  - $\omega_1 = 2\text{x}10^{-8}\ \text{m}^2/\text{V-s}$
  - $\omega_2 = 4\text{x}10^{-8}\ \text{m}^2/\text{V-s}$
  - $\omega_3 = 6\text{x}10^{-8}\ \text{m}^2/\text{V-s}$
- All species are –ve charged
- Flow in x-y plane only

Design of Microfluidic Network Systems – Cont'd

Design case: A CE network system-Cont'd

The **advection equation** in Eq. (10.18) for a 2-dimensional flow in x-y plane is:

$$\frac{\partial C_i}{\partial t}+(V_x+V_{ex})\frac{\partial C_i}{\partial x}+(V_y+V_{ey})\frac{\partial C_i}{\partial y}=\frac{\partial}{\partial x}\left(D_i\frac{\partial C_i}{\partial x}\right)-\frac{\partial}{\partial y}\left(D_i\frac{\partial C_i}{\partial y}\right)+\dot{r}_i \qquad (10.23)$$

where C_i = concentration of specie i in the solution (i = 1,2,3)

t = time into the process

z_i = the valence of ion i.

ω_i = electro-osmotic mobility of the ith specie in Eq. (10-17)

ϕ = externally applied electrical potential

D_i = the diffusion coefficient of the ith specie in the solution

$\dot{r}_i$ = the rate of production of specie i

$V_{ex}=-\omega_i z_i\frac{\partial\phi}{\partial x}$ = the x-component of the electromigration (the "drift velocity")

$V_{ey}=-\omega_i z_i\frac{\partial\phi}{\partial y}$ = the y-component of the electromigration (the "drift velocity")

The electrical field equation becomes: $\frac{\partial}{\partial x}\left(\sigma\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\sigma\frac{\partial\phi}{\partial y}\right)=0$

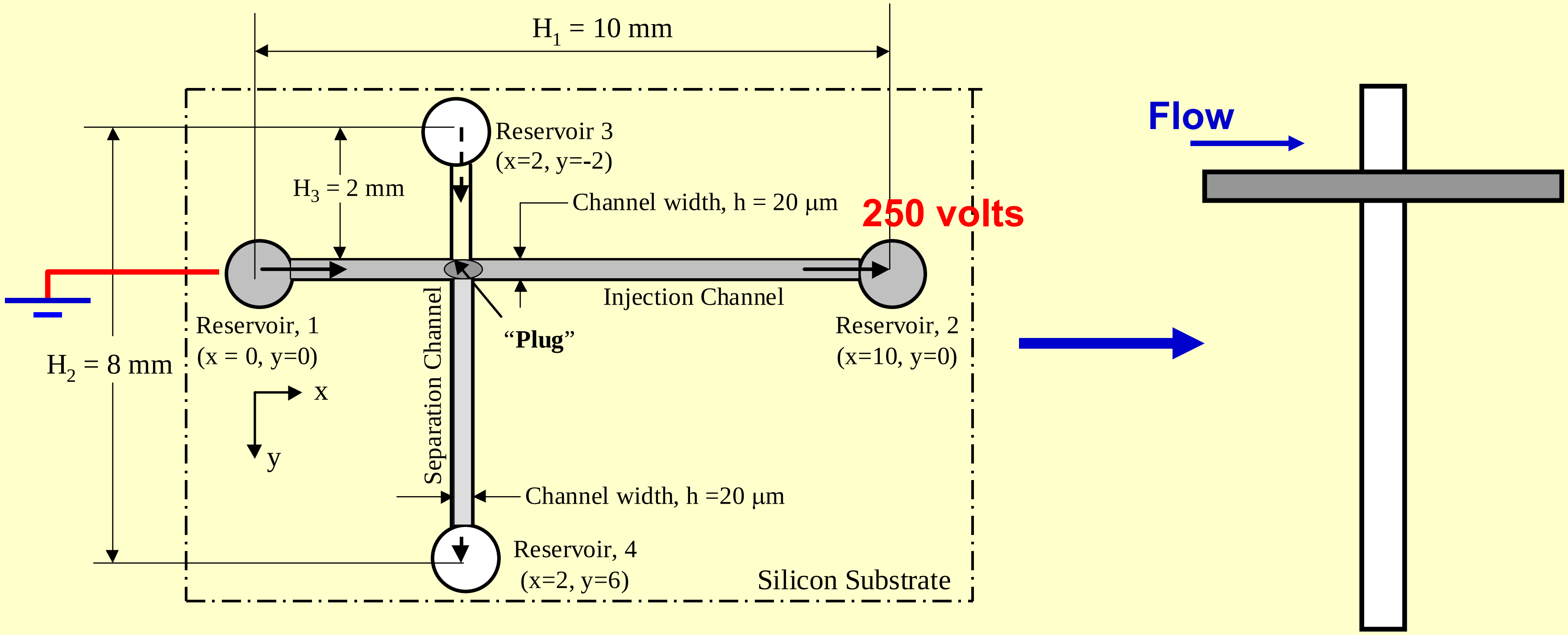
and the electrical conductivity, σ is defined as:

$\sigma=F\sum_i z_i^2\omega_i C_i$ with F = the Faraday's constant = $9.648\text{x}10^4$ C/mol

Design of Microfluidic Network Systems – Cont'd

Design case: A CE network system-Cont'd

(1) Ground the injection Reservoir 1, maintain Reservoir 2 at 250 V:
The injected sample solvent flow from Reservoir 1 to Reservoir 2

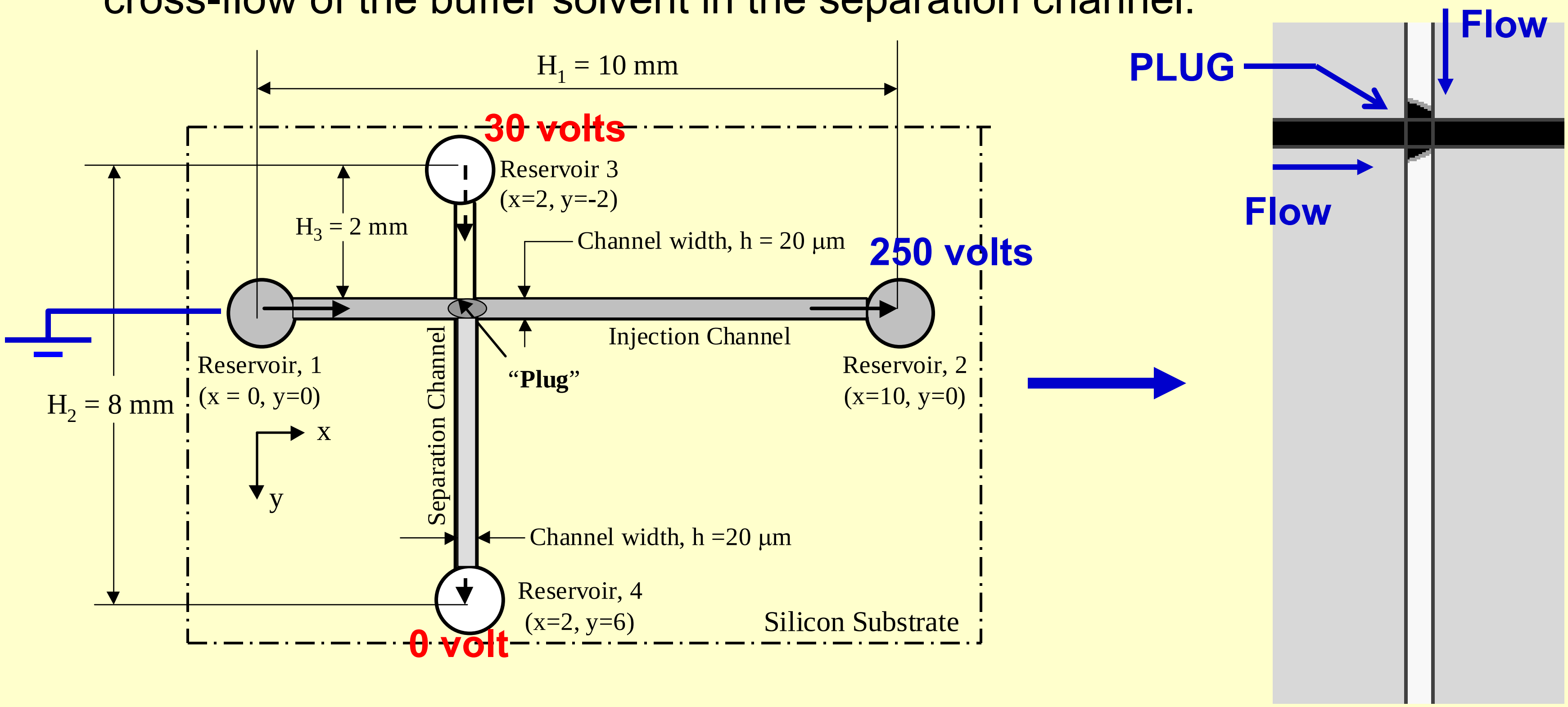


Design of Microfluidic Network Systems – Cont'd

Design case: A CE network system-Cont'd

(2) Apply 30 volts at Reservoir 3 and maintain Reservoir 4 at 0 volt.

A "plug" of the sample solvent in trapezoidal shape occurred at the intersection. The shape of the plug is caused by the "squeeze" of the sample by the cross-flow of the buffer solvent in the separation channel:

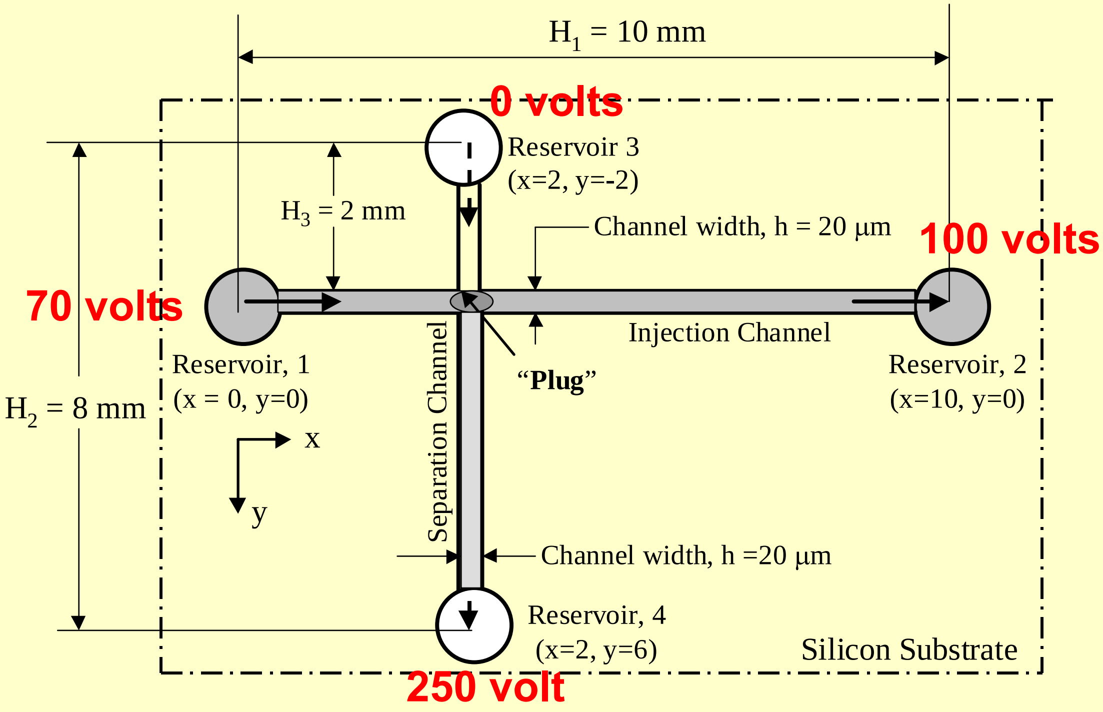


Design of Microfluidic Network Systems – Cont'd

Design case: A CE network system-Cont'd

(3) Begins "Sample-separation" mode.

The weak applied electrical field in the injection channel prevents leakage of sample solvent into the separation channel.

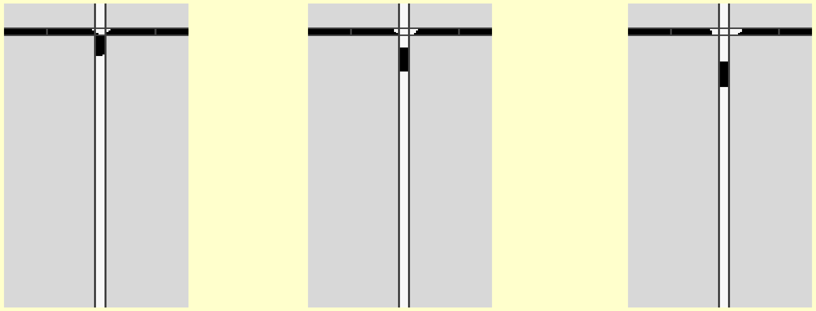


Electromigration of species in the mixed sample solvent (i.e. in the "plug") and the buffer solvent takes place with the strong electrical field applied to the separation channel.

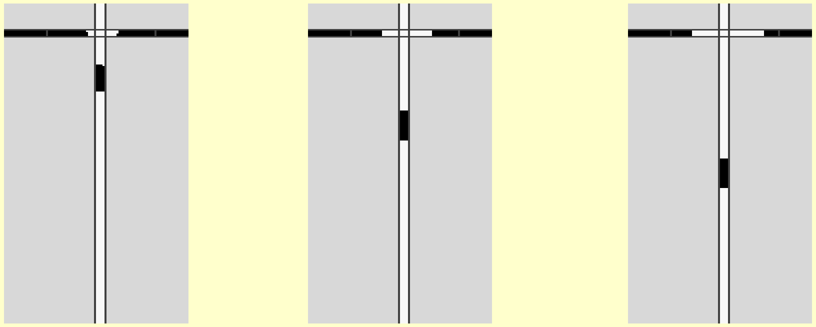
Design of Microfluidic Network Systems – Ends

Design case: A CE network system-ends

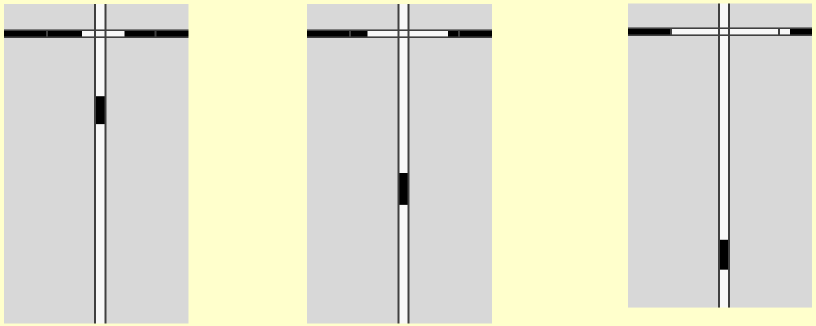
At time t = 0.1 second:

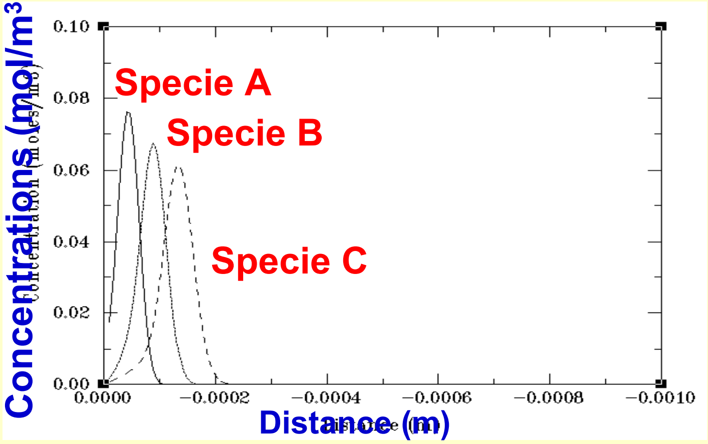


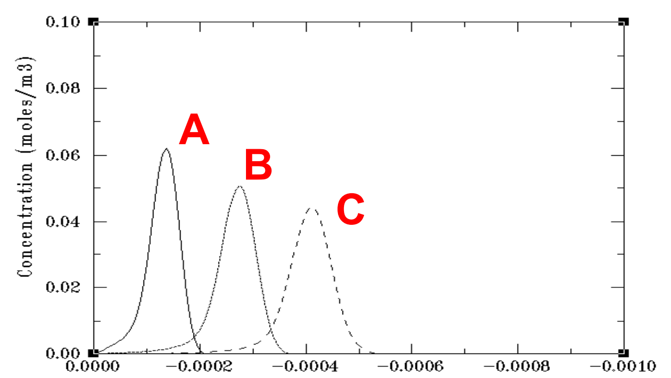
At time t = 0.3 second:

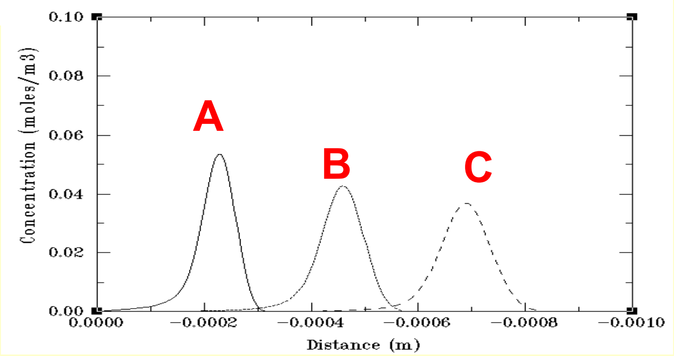


At time t = 0.5 second:









Computer-Aided Design for Microsystems

- **The diversity and complexity of microsystems design used to take as long as 5 years to complete by the industry. Manually designed microsystems is no longer a viable option in practice**

- **It was not until the mid 1990s that computer-aided design (CAD) code was made commercially available to the industry**

- **The design cycle has since drastically reduced to 3 to 6 months for new microsystems products using CAD as a tool**

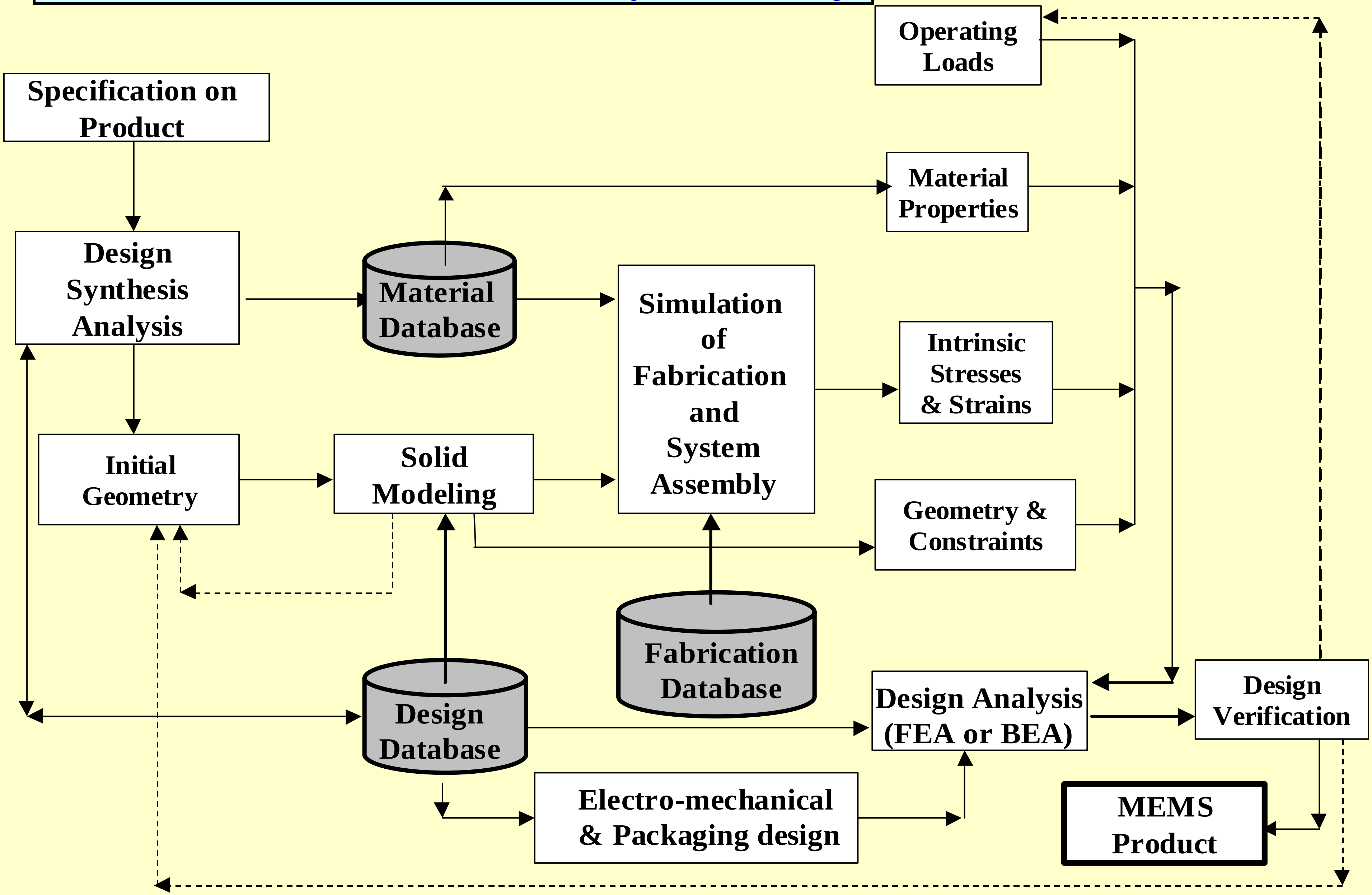
- **IntelliSuite^{TM} and MEMCAD were two commercial CAD packages specifically developed for microsystems design in early years**

- **CAD for microsystems and those for traditional design are radically different in scope**

- **In general, CAD for microsystems involves three (3) major databases:**
  - **electromechanical design database,**
  - **materials database, and**
  - **fabrication database.**

Computer-Aided Design for Microsystems – Cont'd

General structure of CAD for microsystems design



Computer-Aided Design for Microsystems – Cont'd

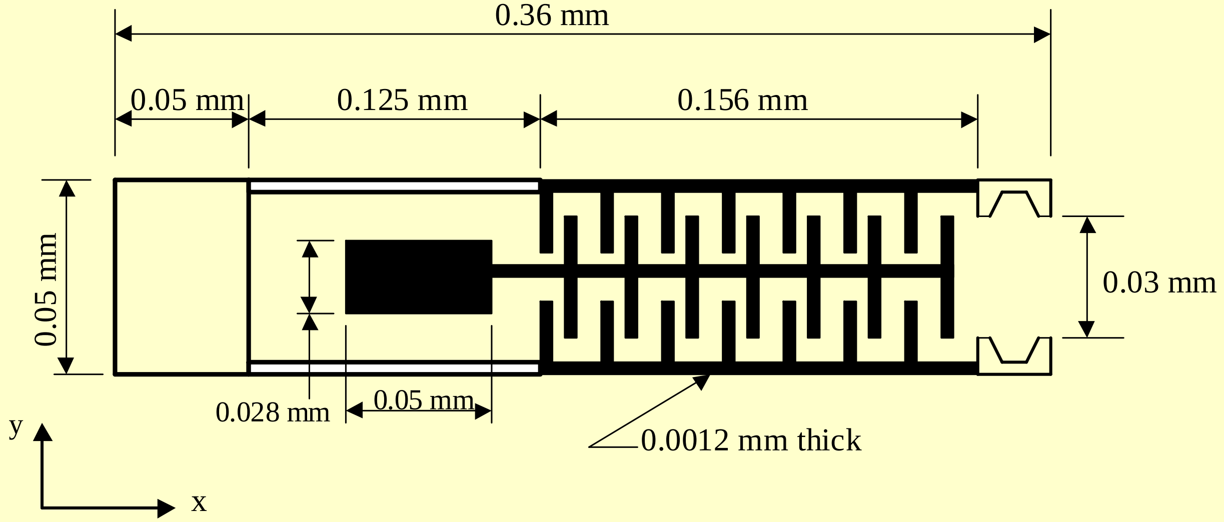
Selection of a CAD package:

- User friendliness
- The adaptability of the package to various computer and peripherals
- Interface of this CAD package with other software, e.g. nonlinear thermomechanical analyses and the integration of electric circuit design
- Completeness of material database in the package
- The versatility of the built-in finite element or boundary element codes
- Pre- and post-processing of design analyses by the package
- Capability of producing masks from solid models
- Provision for design optimization
- Simulation and animation capability
- Cost in purchasing or licensing and maintenance

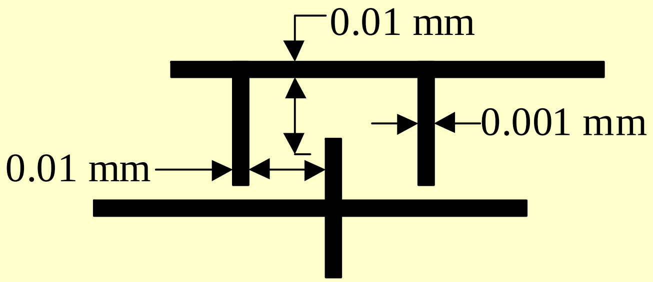
Computer-Aided Design for Microsystems – Cont'd

Design case using IntelliSuite code

The case involved the design of a micro gripper with a plan view:



with the gap of electrodes arranged as follows:



Computer-Aided Design for Microsystems – Cont'd

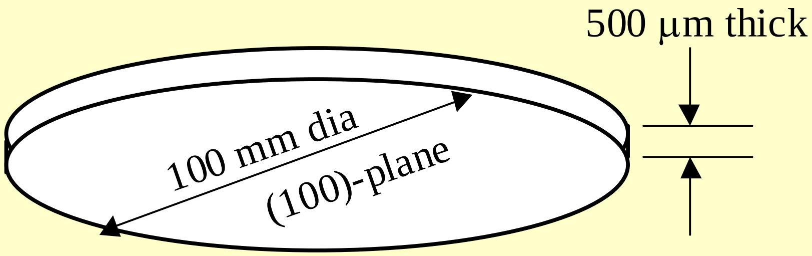
Design case using IntelliSuite code – Cont'd

Major steps in the design case:

Step 1: Substrate selection:

- Silicon wafer is chosen because of the relatively modest cost.
- The wafer is the standard 100-mm diameter with 500 μm thick sliced from a single silicon crystal boule produced by Czochralski method.
- The surface of the wafer is normal to the <100> orientation as illustrated:

Silicon wafer substrate:



Computer-Aided Design for Microsystems – Cont'd

Design case using IntelliSuite code – Cont'd

Step 2: Substrate cleaning:

- The Code recommends using Pirahna solvent for cleaning the wafer surface. This was one of several options offered by the CAD Code. This solvent contains 75% H_2SO_4 and 25% H_2O_2. The substrate is submerged in the solvent for 10 minutes.
- The cleaned wafer is ready for oxidation on one of its surfaces

Step 3: Create a SiO_2 layer by dry oxidation:

- A 1 μm thick SiO_2 layer is deposited on the surface of the wafer to serve as an electrical insulator between the anode and the cathode in the electrostatic actuation of the cell gripper
- The deposition takes place in a "furnace" at the temperature of 1100^{o}C at a pressure of 101 KPa as indicated by the CAD Code

Computer-Aided Design for Microsystems – Cont'd

Design case using IntelliSuite code – Cont'd

Step 4: LPCVD deposition of polysilicon structure layer:

- Polysilicon is chosen to be the cell gripper structure
- A 1.2 μm thick is deposited over the oxide layer with a medium temperature
- LPCVD process with detail parameters provided by the IntelliSuite^{TM} code
- The deposition temperature is in the range of 500-900^{o}C, with an annealing temperature of 1050^{o}C (as by the Code)
- The CAD Code also specified 60 minutes to be the required time for this process.

Step 5: Aluminum sputtering:

- An aluminum film is deposited for the lead wire for conducting electrical current through the electrodes
- A 3-μm thick film is sputtered onto the polysilicon layer
- Estimated time for this process is 10 minutes (as by the Code)

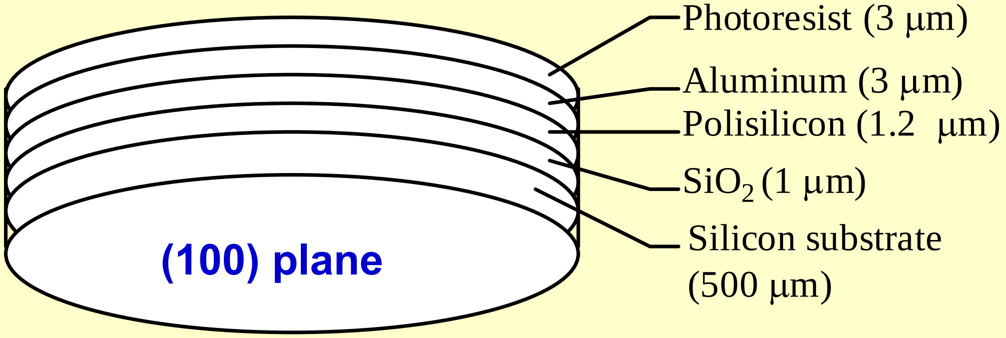
Computer-Aided Design for Microsystems – Cont'd

Design case using IntelliSuite code – Cont'd

Step 6: Application of photoresist:

- Positive photoresist is applied to the aluminum layer
- A 4000-rpm spinning speed of the chuck as illustrated in Fig. 8.3 is used to spread the photoresist.
- The photoresist-covered substrate assembly is baked at 115°C results in a 3-μm thick layer
- All films, including the photoresist, deposited on the silicon wafer:

Thin film layers for a cell gripper construction:



Computer-Aided Design for Microsystems – Cont'd

Design case using IntelliSuite code – Cont'd

Step 7: Photolithography by UV exposure:

- A photolithographic process using a UV light source at 250 watts with a wavelength, λ = 436 nm is used in the process over a Mask 202 created for anode and cathode. Exposure time in this case is 10 seconds

Step 8: Wet etching to remove photoresist:

- The solvent KOH described in Chapter 8 is used as the etchant to removed the exposed photoresist
- The unexposed resist stays attached to the aluminum layer

Step 9: Wet etching on aluminum:

- A special etchant is selected to remove the unprotected aluminum from the surface
- This etchant contains 75% H_2SO_4, 20% $C_2H_4O_2$ and 5% HNO_3
- The depth of the aluminum layer to be removed is 3 μm
- Estimated time for this process is 15 minutes (as by the Code)

Computer-Aided Design for Microsystems – Cont'd

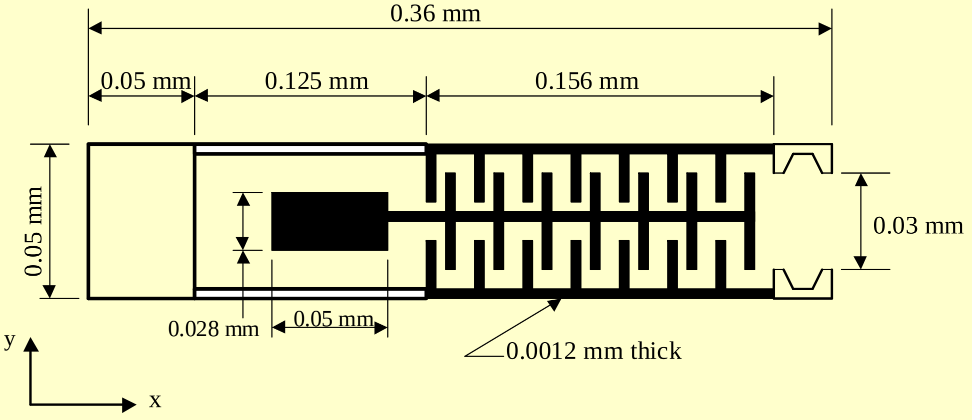
Design case using IntelliSuite code – Cont'd

Step 10: Wet etch to remove photoresist from aluminum:

- Once again, KOH is used to remove the photoresist left on the surface of aluminum anode and cathode

Step 11: Photoresist deposition and photolithography of gripper structure:

- Positive photoresist is applied to the entire surface of the wafer following the same procedure in Step 6
- Another mask that outlines the gripper structure is used for photolithography following the same procedure in Step 7:



Computer-Aided Design for Microsystems – Cont'd

Design case using IntelliSuite code – Cont'd

Step 12: Remove photoresist by wet etch:

- The same procedure as described in Step 10 is used for this purpose

Step 13: Etch polysilicon by reactive ion etching (RIE):

- RIE is chosen to remove the unprotected region of the polysilicon layer for the net shape of the gripper structure
- The reactive chemical species with chlorine or fluorine in plasma is involved in this process

Step 14: Remove the SiO_2 sacrificial layer:

- This process involves the use of wet etching in conjunction with a laser photochemical etching process
- This etching process uses a SiH_4 etchant and a KrF laser at 0.3 J/cm^2 intensity
- The combined etching provides an etching rate of 40 A/s (as by the Code)
- The process in this step releases the gripper arms and tips from the SiO_2 layer

Computer-Aided Design for Microsystems – Cont'd

Design case using IntelliSuite code – Cont'd

Step 15: Separation of gripper and the substrate:

- The net shape of the structure after Step 14 is the gripper structure attached to the silicon substrate of the same structural outline bonded by a thin SiO_2 film
- Separation of the gripper structure from the substrate requires the removal of the in-between SiO_2 layer (a sacrifice layer)
- The removal of this thin layer can be accomplished either by a thin diamond saw, or by using the "etch pit" technique

Step 16: Eelectromechanical analysis:

- The purpose of this analysis is to assess whether the gripper fabricated by the above processes would perform the desired functions
- The Intellisuite code can perform computer-simulated gripper operations with animation with applied electrical field e.g. the charge density resulting in different gripping effects of the gripper
- Animation options are available for visual verifications of the gripper design

Computer-Aided Design for Microsystems – Ends

Design case using IntelliSuite code – Ends

An electromechanical analysis is then performed using that provision of the code to ensure structural integrity.

A solid model of the gripper is established after all design criteria are met: