Green Electronics

Lectures Slides

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Spring 2020

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Lecture 1
Electronic Industry and the Environment

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Course Information

- Website:
  - http://scholar.cu.edu.eg/hmostafa/classes
- Office hours by email appointments
- Instructor office:
  - Electronics & Communications building, 4th floor
- This course part
  - Cover the following:
    - Electronic industry and the environment
    - Green nanotechnology
    - Nanotechnology manufacturing
    - Investigation tools
    - CMOS/MEMS Fabrication
    - MEMS Applications

Course Information

- Textbook reference:
  - Course lecture slides
  - An Introduction to Microelectromechanical Systems Engineering (Artech House Mems Library) by Nadim Maluf
- Course Project
  - Turning our EECE department knowledge to a real charity projects and show/feel our impact ☺.
  - More details will be given shortly
- Course work grading
  - 15% Course Project including video
  - 5% COMSOL Project
  - 10% Midterm

Hazards of Electronics Industry

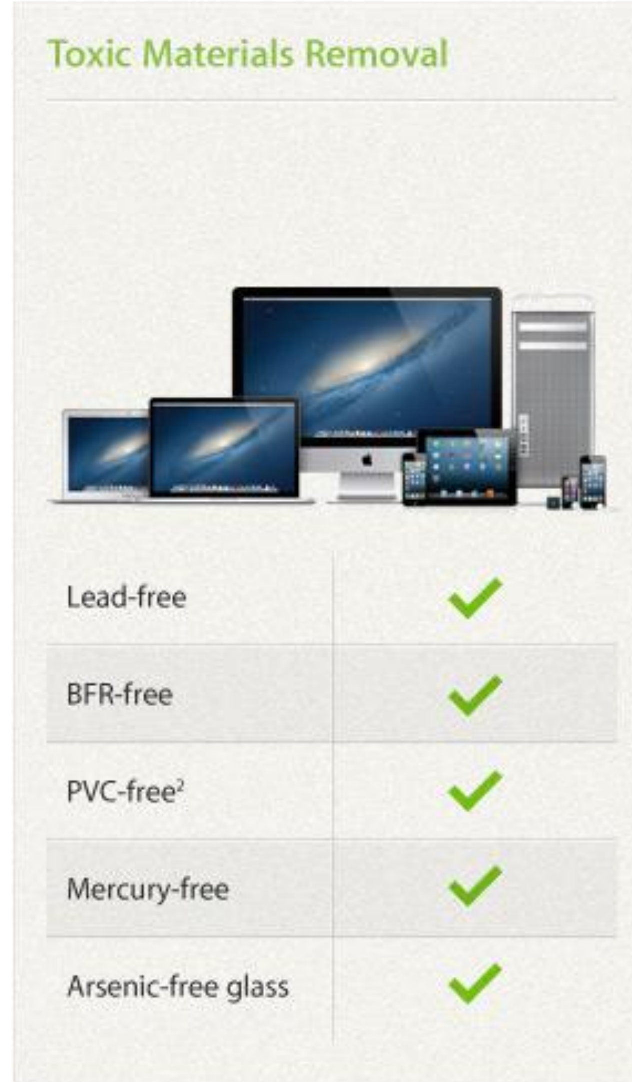
- Electronics industry has some toxic materials
- Threat to the environment and human life

Hazards of Electronics Industry

- 90% of electronic devices contain LEAD
  - LEAD is used in soldering

Hazards of Electronics Industry

- Other toxic materials such as
  - Chlorinated materials
  - Acids
  - Plastics
  - Mercury
  - Arsenic
  - .
  - .
  - .
  - .



Hazards of Electronics Industry

- Three fold threat to the environment
  - Manufacturing

Hazards of Electronics Industry

- Three fold threat to the environment
  - Manufacturing
  - Utilization and handling

Hazards of Electronics Industry

- Three fold threat to the environment
  - Manufacturing
  - Utilization and handling
  - Disposing

What is Green about Electronics

- Use less toxic materials in the industry
  - Less than 1 ppm for lead
  - Targeting lead-free assembly

Electronic Waste

- **Environmental Protection Agency (EPA) reported that in US alone:**
  - 5-7 million tons of electronic devices (i.e., PCs, TVs, mobile phones, MP3s) are scrapped
  - 400 million kg of lead are contained in obsolete PCs
  - A large source of cadmium is found in rechargeable Nickel Cadmium (Ni-Cd batteries) found in laptops and cell phones
- **What do we do with the e-waste?????**



Electronic Toxins

- Lead is one of the most dangerous elements
- lead precipitates in bones and in soft tissues and causes brain, blood and kidney damage
- High exposure to lead results in lead poisoning
  - anemia, retardation, coma and even death

Electronic Toxins

- **Why Lead** ?
  - **can be easily remolded and refined**
  - **has the highest recycling rate of all industrial metals in the world**
  - **has low melting point, high strength, high ductility (flexibility)**
  - **has high fatigue resistance (repeated stress/loading)**
  - **long life**
- **Can we have lead-free products at reasonable cost?????**

Disposal of E-Waste

- **E-waste = all obsolete PCs, entertainment device electronics, mobile phones, TV sets, and even refrigerators and other household appliances**
- **Rapid changes in technology have resulted in a fast growing surplus of e-waste**
- **E-waste can be disposed in three way :**
  - **Land-filling**
  - **Incineration**
  - **Recycling**

Disposal of E-Waste

- Land-filling
  - disposing the e-waste by burying
  - certain amount of chemical leaching and metal leaching does occur
    - Mercury leaches when certain electronic devices such as circuit breakers are destroyed
  - Leaching toxins into soil and spill into ground water, contaminating our food and water supply

Disposal of E-Waste

- **Incineration**
  - destroying e-waste by burning in special containers called incinerators
  - causes toxic fumes to be emitted
  - direct threat to human life and to the ozone layer


Disposal of E-Waste

- **Recycling**
  - **Removing the hazardous waste into secondary products that eventually have to be disposed of at a much later time**
  - **Some hazardous emissions to the air also result from recycling the e-waste containing heavy metals such as lead and cadmium**
    - **Pose significant risk to workers and communities nearby**
  - **Only 15-20% of e-waste is recycled**
  - **Electronic devices contain valuable elements including gold, silver, platinum and copper**

IQ Question

V.

4	5	7	3
8	3	3	9
7	6	9	5
6	9	8	?

What number should replace the question mark?

IQ Question

V.

4	5	7	3
8	3	3	9
7	6	9	5
6	9	8	?

What number should replace the question mark?

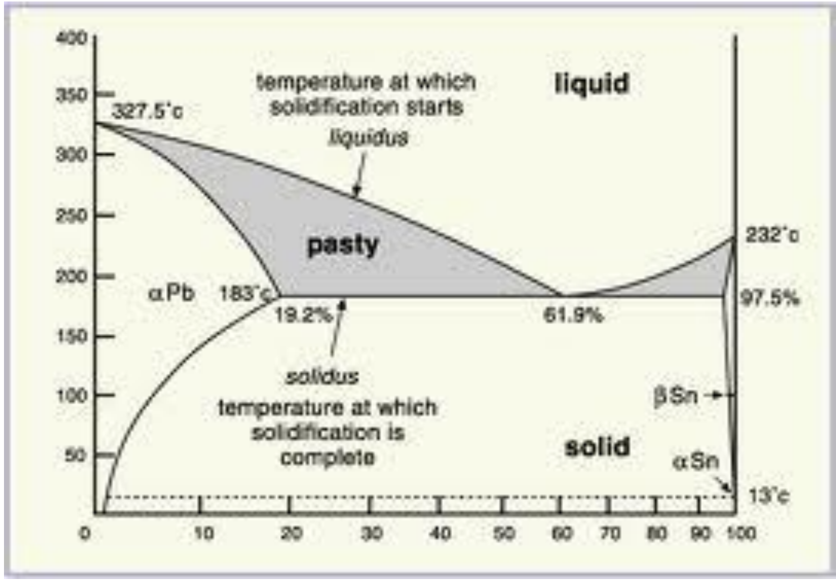
Answer: 8

Explanation:

The sum of the numbers in each line across increases by 4.

Interconnection Solder Properties

- Solder is a fusible metal alloy with low melting point to join metal surface
- Nearly all electronic systems are known to use tin-lead solder alloy for assembly phase
- The tin-lead system forms a simple eutectic. At a certain composition (called eutectic composition {61.9% tin and 38.1% lead}) the alloy melts at a single temperature (called eutectic temperature) = 183^{o}C



Conversion to Lead-Free Assembly

- The driving force for the conversion to lead-free manufacturing and recycling is RoHS (Restriction of Hazardous Substances)
- ROHS restricts the use of lead (Pb) ,mercury (Hg), cadmium (Cd)..etc.
- A viable tin-lead replacement is Sn-Ag-Cu (SAC) compound alloy with variation in the silver content (3.0 % and 4.0%)

Conversion to Lead-Free Assembly

- SAC alloy (96.5% Sn, 3% Ag, 0.5% Cu) which is referred to as SAC305 is accepted now as a standard lead free replacement for tin-lead
- The SAC 305 alloy melts between 217ºC – 221ºC as compared with tin-lead alloy which melts at 183ºC
- PCB design should change the temperature rating to 260ºC (higher reflow temperatures) as compared to the current typical rating of 230ºC associated with tin-lead

Going Green

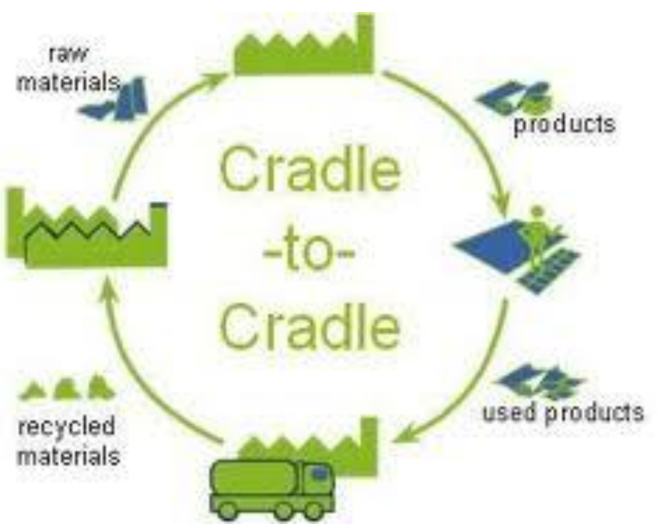
- If the product (due to lead-free design) is weird during handling, it will make the product difficult to market.
- The use of new materials may require a circuit redesign which is an added cost.
- Initially, replacement materials will cost more since the supply is low and processing has not yet been optimized.

Green technology

- Green electronics means products and components that have minimum adverse environmental effects throughout their life cycle, which means
  - no harmful materials are used
  - eco-efficient and environment-friendly manufacture processes are adopted
  - less power is consumed in operation and stand by modes
  - fully recyclable with no hazardous waste or emission

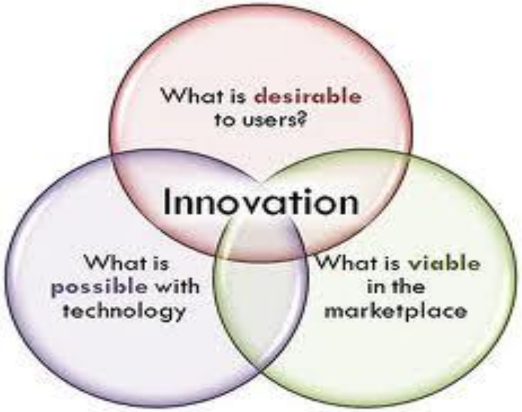
Green technology

- **Guidelines for the green electronics**
  - **Sustainability**
    - meeting the needs of society in ways that can continue indefinitely into the future
  - **Cradle to cradle design**
    - ending the cradle to grave cycle of manufacturing by creating products that can be fully reclaimed or reused or recycled



Green technology

- **Guidelines for the green electronics**
  - **Source reduction**
    - reducing waste and pollution by changing patterns of production and consumption
  - **Innovation**
    - developing alternatives to technologies
  - **Viability**
    - creating economic activity and creating new careers in industries that are friendly to the environment



What is Nanotechnology

- **1 nm = 10^{-9} m**
- **Nanomaterials have**
  - higher strength
    - less material is needed to accomplish a given task
  - different electromagnetic properties
    - develop new energy converters and generators
  - manageable permeability to fluids
    - improved filtering technology to remove undesired substances from water or air
- **Nanotechnology enables us to achieve material properties that were previously unattainable, impractical or too expensive**
- **Nanotechnology concerned with using materials and technologies which will lead to better alternatives to non green products**

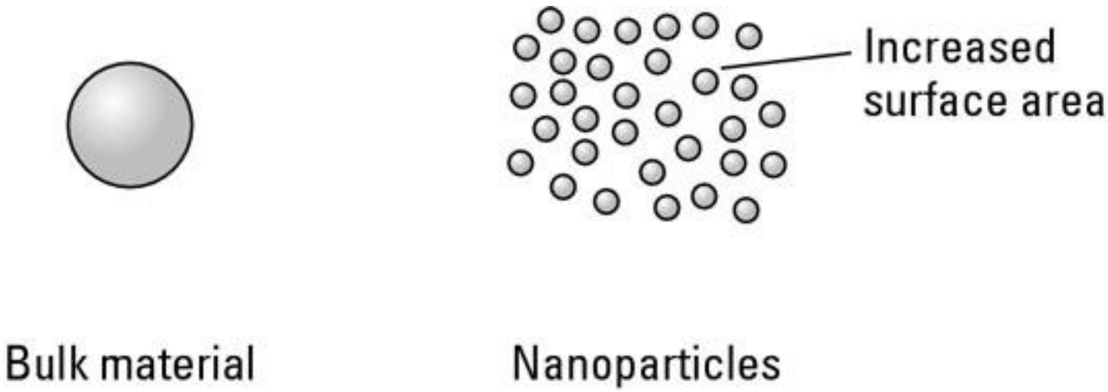
Challenges and Opportunities

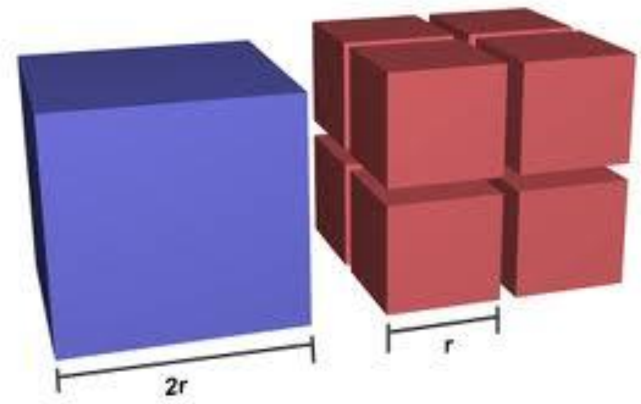
- **Nanotechnology is a way to**
  - provide sustainable energy at affordable prices
  - provide clean water and cleanse unclean water
  - provide a clean environment and cleanse it from existing contamination.

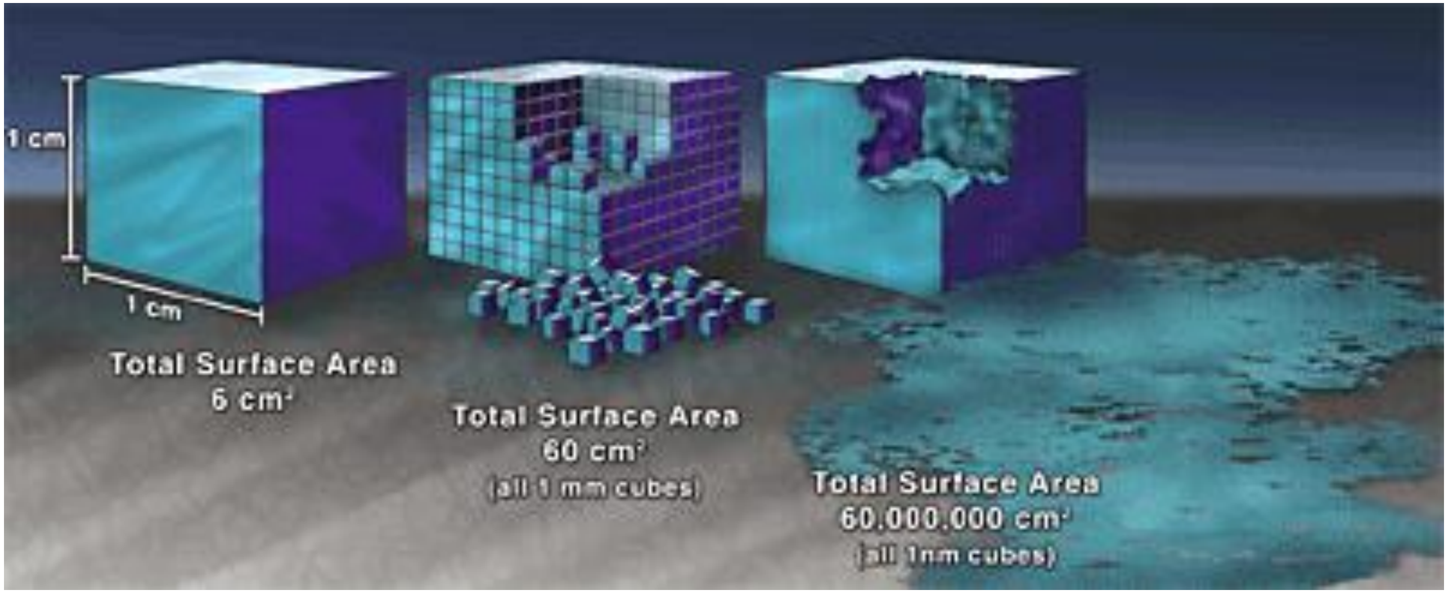
Complexity Engineering

- Nanoscience is about understanding the complexity and then develop the ability to engineer complex systems
- Materials with internal nanostructures can have inner surfaces that sum up to very large areas.
  - The surface area of the individual boundaries of a large number of nanoparticles can have a huge total surface area many orders of magnitude larger than the area of the container containing them
  - If such materials were to come commonplace in construction one would need less iron, steel and concrete which are very energy and resource intensive to produce

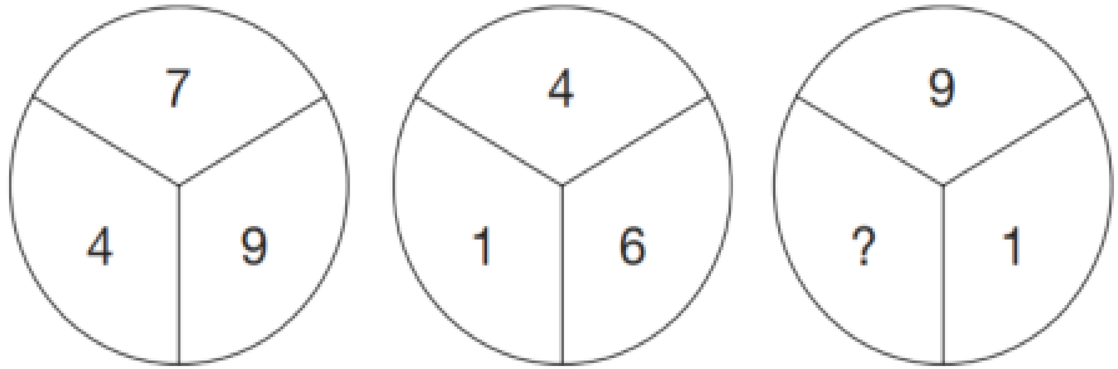
Complexity Engineering







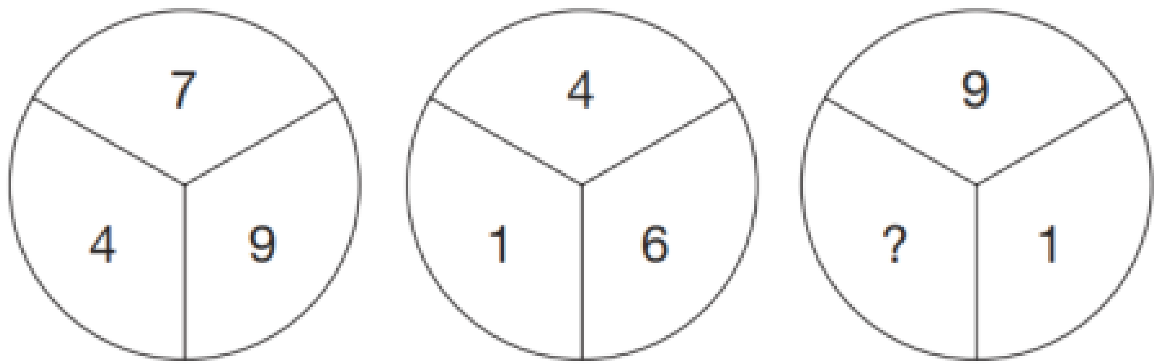
Lecture Pause



What number should replace the question mark?

Answer:

Lecture Pause



What number should replace the question mark?

Answer: 8

How green are Nanomaterials??

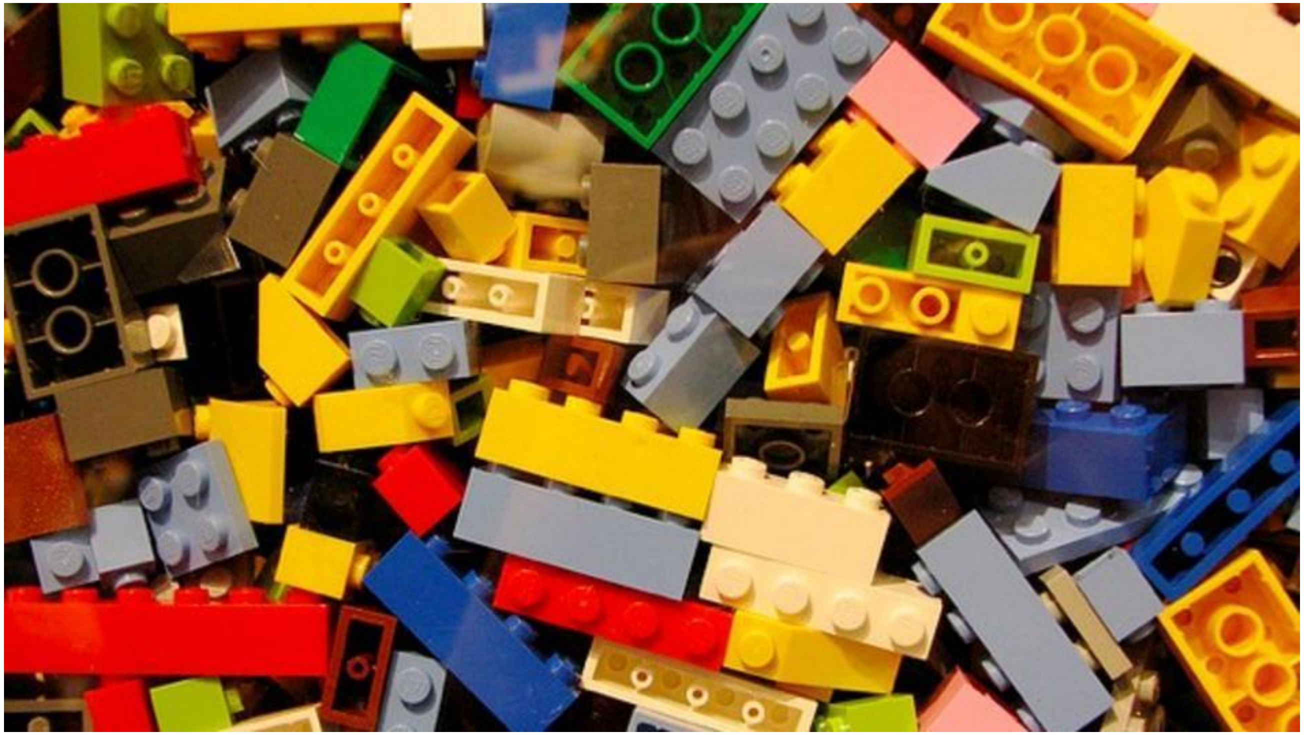
- Top-Down and Bottom-Up nano-fab

Top–Down and Bottom-Up

- **Top-Down**
  - Start from bulk substrate and remove materials to form the desired structure
  - Similar to forming a statue from a large rock
  - Example: Photo-lithography

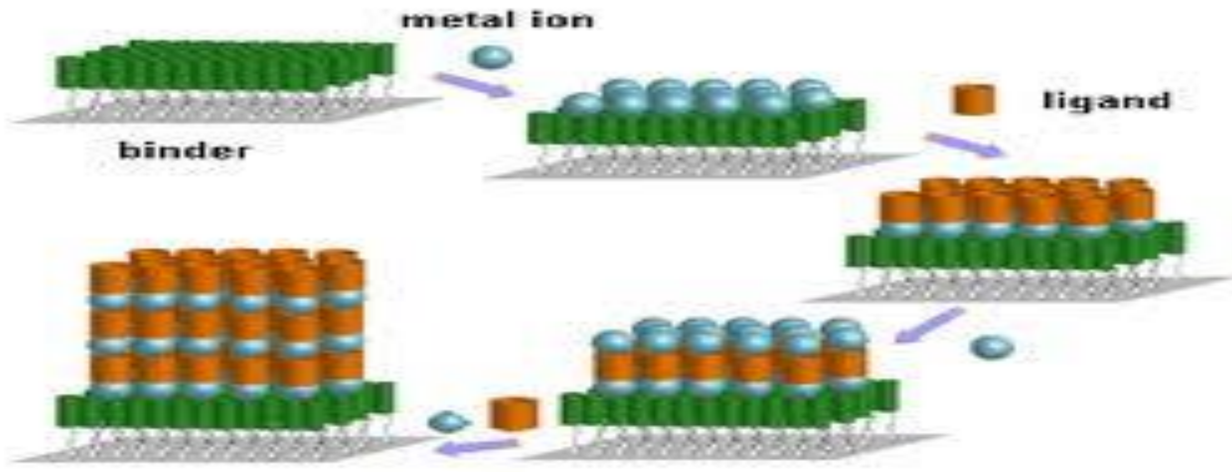
Micro/Nano Fabrication

- **Bottom-Up**
  - Start from atoms to form the desired structure
  - Similar to LEGO bricks



How green are Nanomaterials??

- Top-Down and Bottom-Up nano-fab
- In Nanotechnology, Nanomaterials with specially tailored properties, modified by ultra fine particle size, crystallinity, structure or surface condition <Botom-Up>



Limitations on Sizes of Electronic Components

- CMOS technology scaling results in several challenges such as process variations due to the photolithography limits.
- Currently, 7nm CMOS transistor is being commercial.
- The end of the CMOS is very close!!!
- New Nanoelectronics devices are innovative with Nanotechnology
- But, what is Photolithography and what are its limits…

CMOS scaling

Obligatory Moore's "Law" Slide:

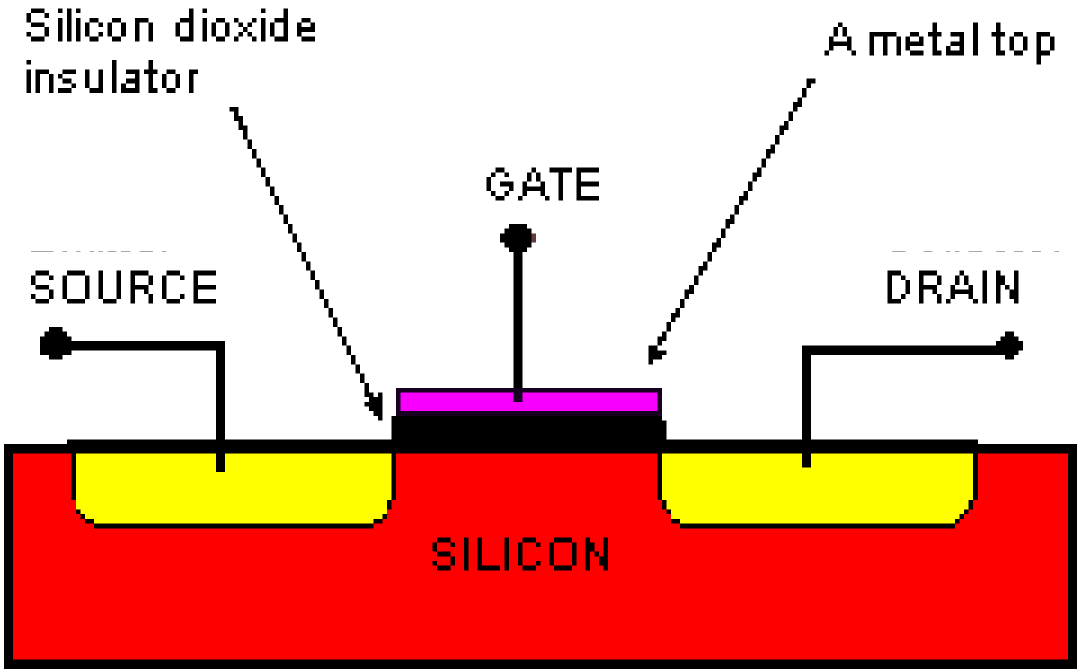
"Computing Power will double every 18 months"

"Number of transistors on a chip will double every 12-18-24 months "

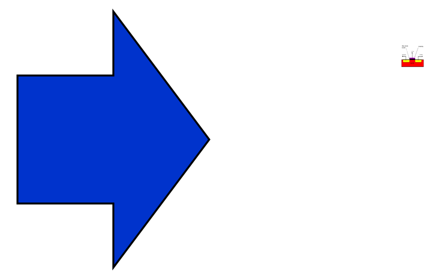
"Transistor channel length will shrink by 50% every 36 months"

"Intel Net Corporate Worth will double every 18 months"

CMOS scaling



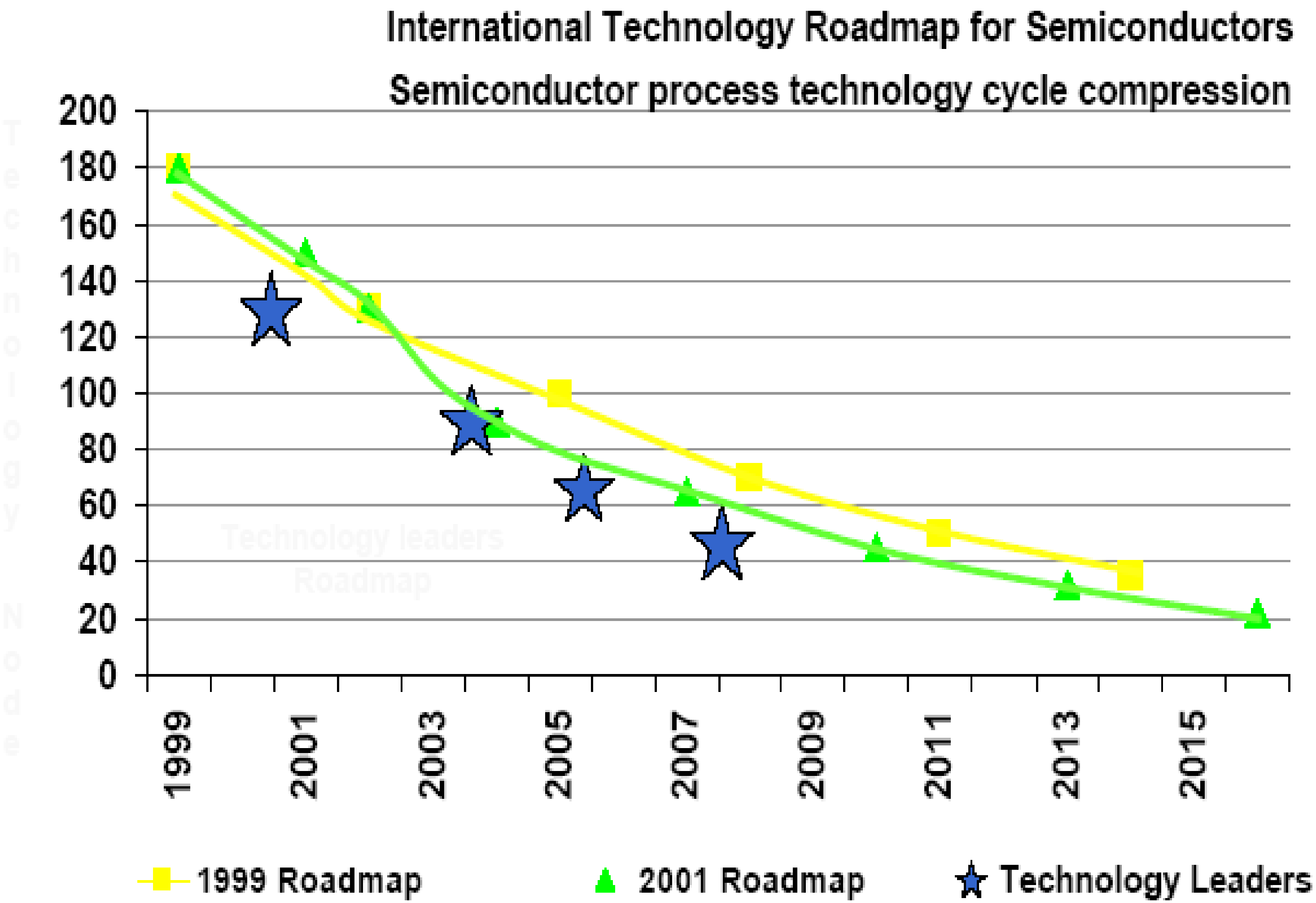
(2000) 180nm transistor



(2020) 3nm transistor

CMOS scaling will not stay forever, but forever can be delayed

CMOS scaling



Green Electronics

Lecture 2
Photolithography/Etching

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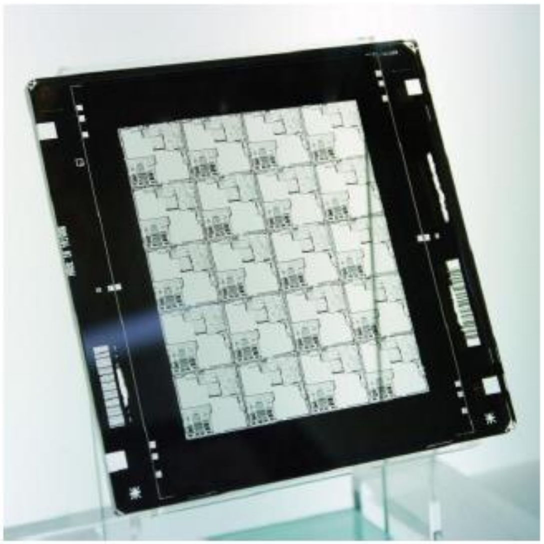
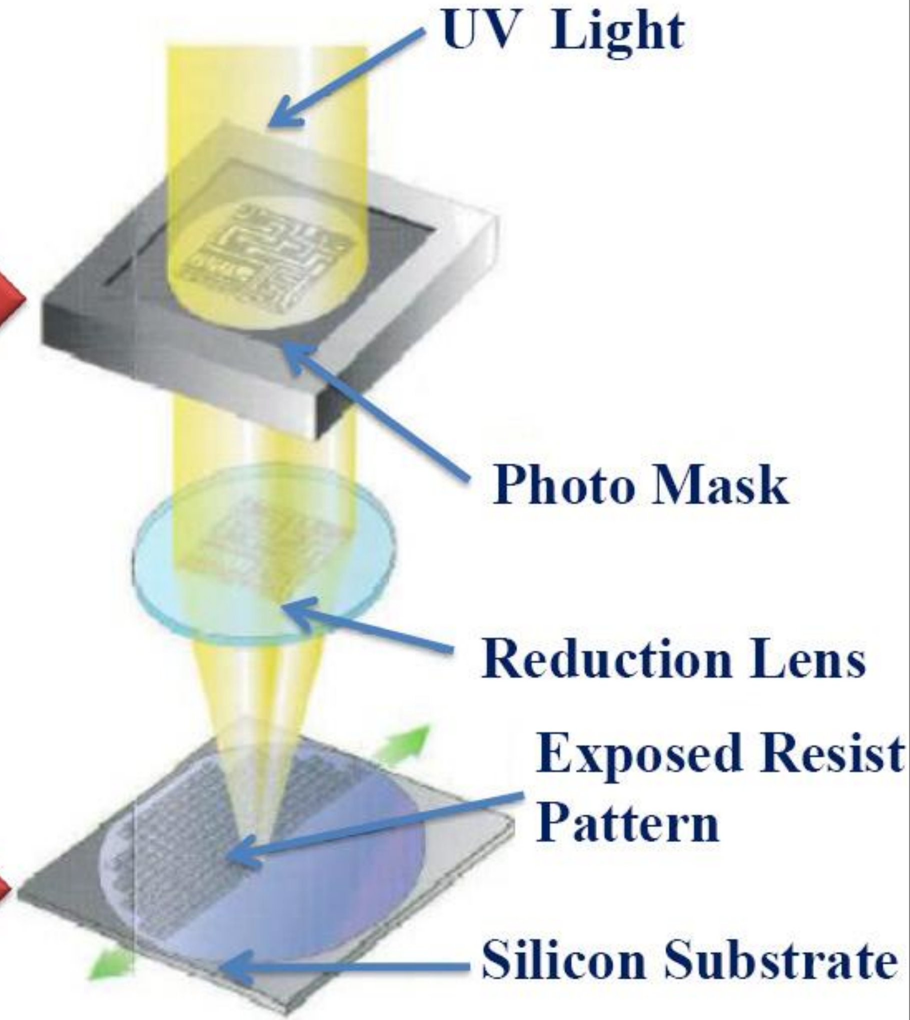
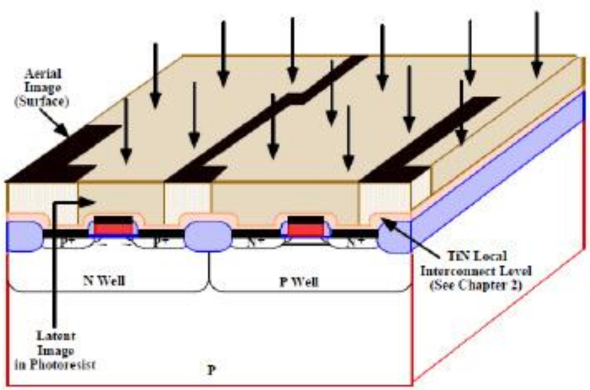
Photolithography

- **Photolithography** is the **cornerstone** of modern **IC manufacturing**.

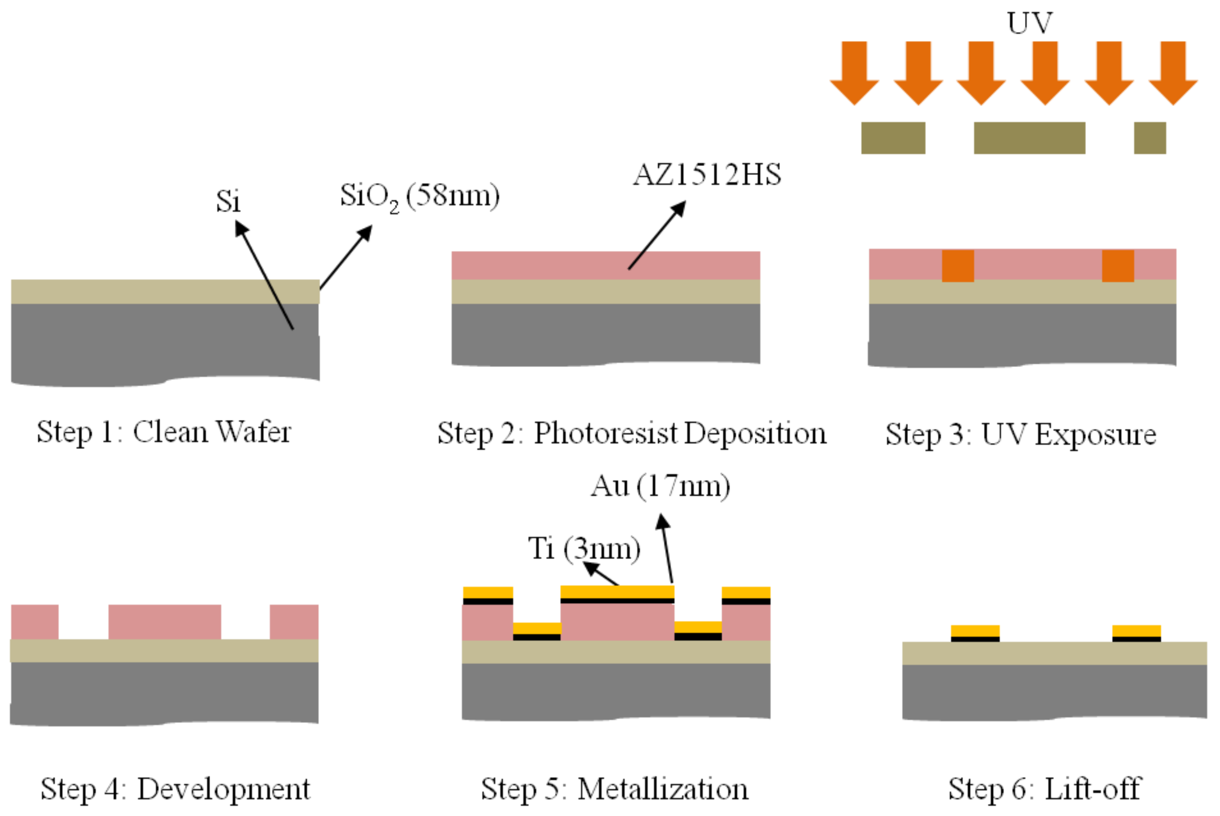






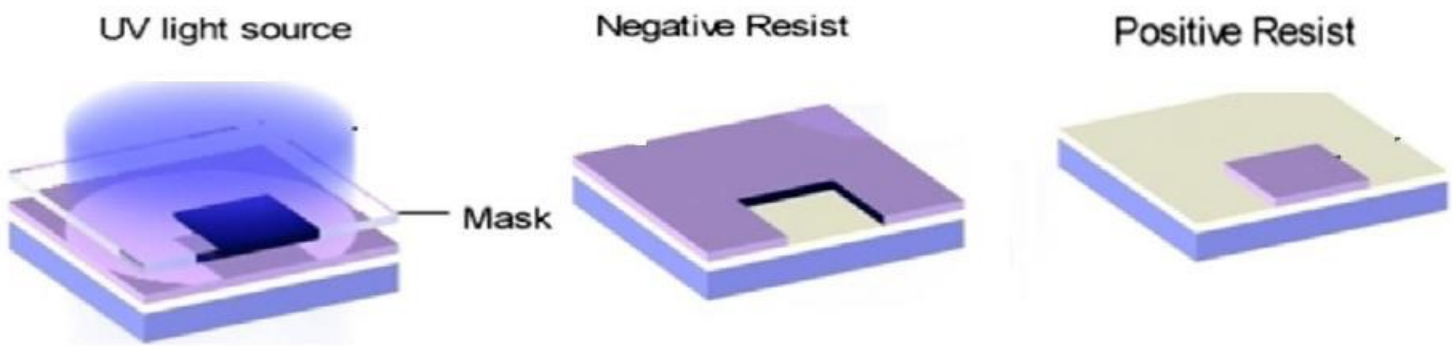
Photolithography

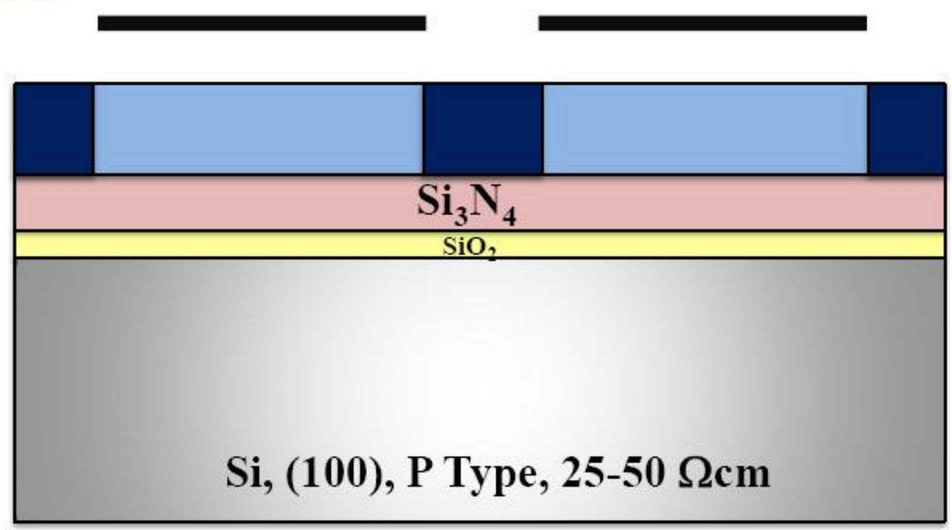
- Coat, protect, expose, etch, repeat…



Photolithography

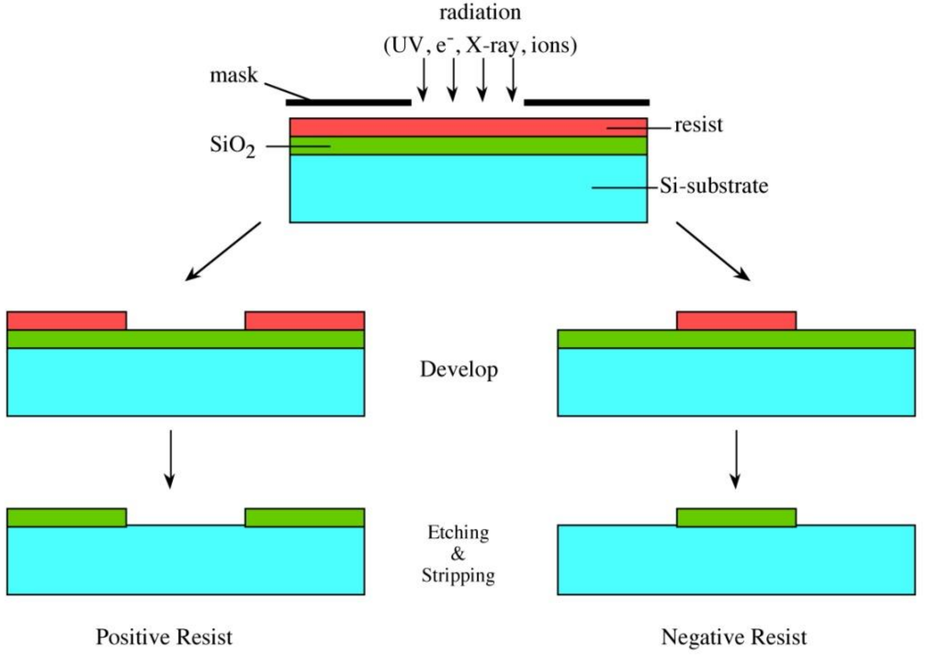
- **Positive resist**
  - **The molecule** in the resist which is sensitive to light, **absorbs UV** photons and **changes its chemical structure** in response to light.





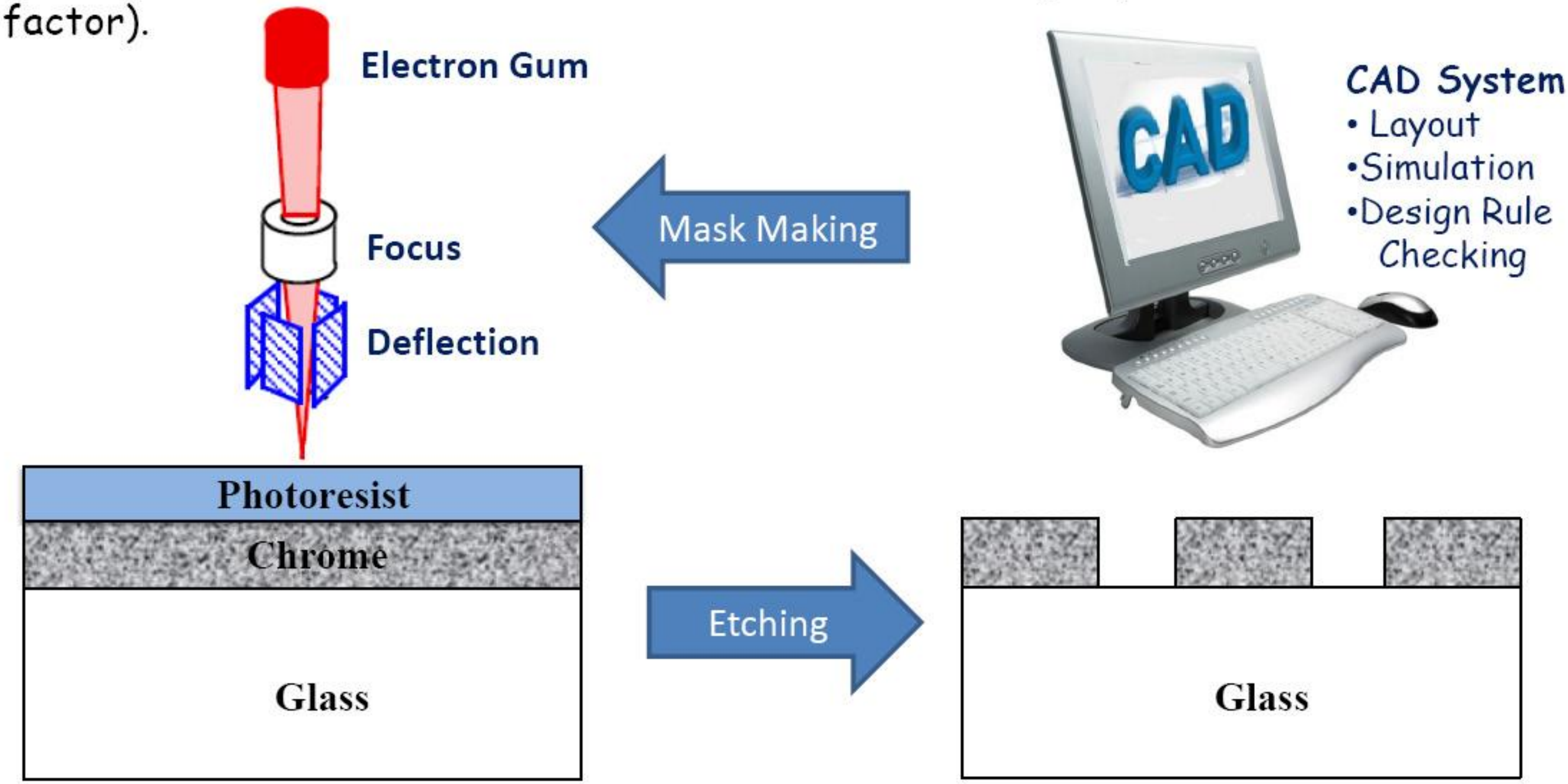
Lithography

- **Lithography**
  - Positive photoresist
    - Exposed area is dissolved and the unexposed area remains
  - Negative photoresist
    - Exposed area remains and the unexposed area is dissolved



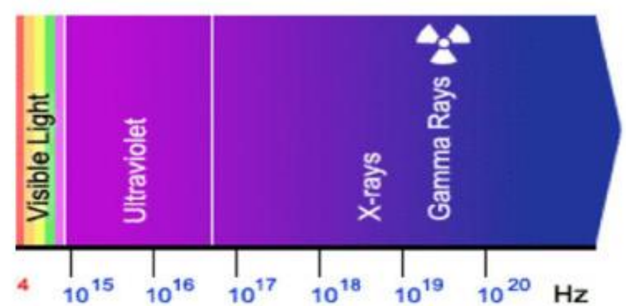
Mask Fabrication

- **Thin layer** (≈ 80nm) of **chrome** and **photoresist** deposited on **high quality glass**.
- **Patterns** are **generated** using **electron beam** or **laser**.
- The mask is fabricated with **pattern dimensions 4X** to **5X** larger than the **features actually desired** on the **wafer** (it will be reduced during exposure with the same factor).



Light Sources

- Higher resolution lithography requires shorter wavelength photons; **decreasing feature sizes require shorter wavelengths**, λ.
- Historically, most lithography systems have used mercury (Hg) vapor lamps which generate many spectral lines from a high intensity plasma inside a glass lamp.
  - Electrons are excited to higher energy level by collisions in plasma.
  - When these electrons drop back to their lower energy state photons are emitted which **characteristic** of the allowed **energy levels** in the **Hg atom**.
  - (**g line**) λ = 436 nm (typical in 1990's)
  - (i **line**) λ = 365 nm (used for 0.5 µm, 0.35 µm **Resolution**)
- Excimer lasers (Excited dimer) is used to generate photons in the deep UV part of the spectrum.
- Two that are of specific interest for lithography are KrF (Krypton Fluorine) and ArF (Argon Fluorine)

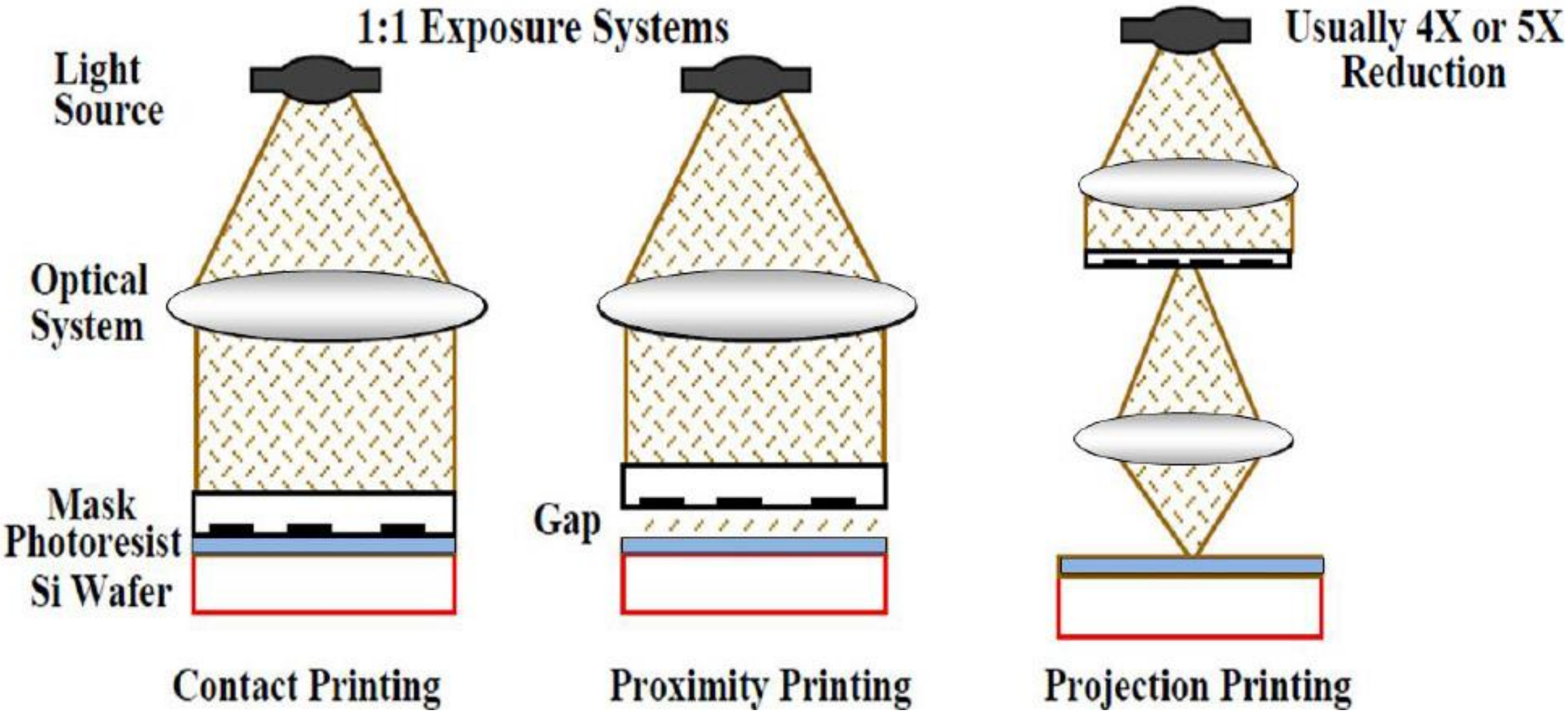


- krF λ = 248 nm (used for 0.25 µm, 0.18 µm, 0.13 µm)
- ArF λ = 193 nm (used for 0.13 µm, 0.09 µm)

❑λ = 157nm, is currently used for sub-90nm CMOS

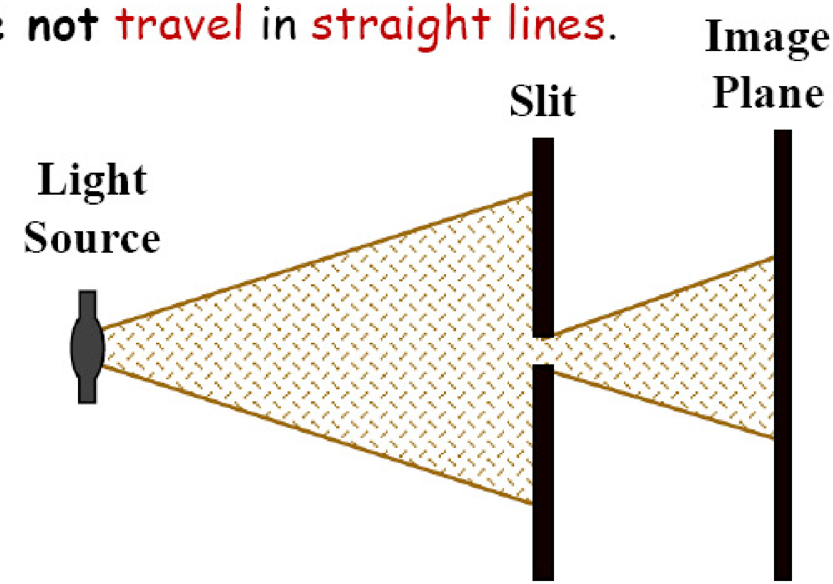
Wafer Exposure Systems

- **Contact printing:** the mask is placed chrome side down in direct contact with the resist layer on the wafer; high-resolution, hard contact results in damage to both the mask and the resist layer.
- **Proximity printing:** the mask and wafer are kept separated by 5 – 25 μm ; it is not possible to print features smaller than a few μm with UV (except for X-ray).
- **Projection printing:** theses systems provide high resolution but without the defect problems of contact printing.

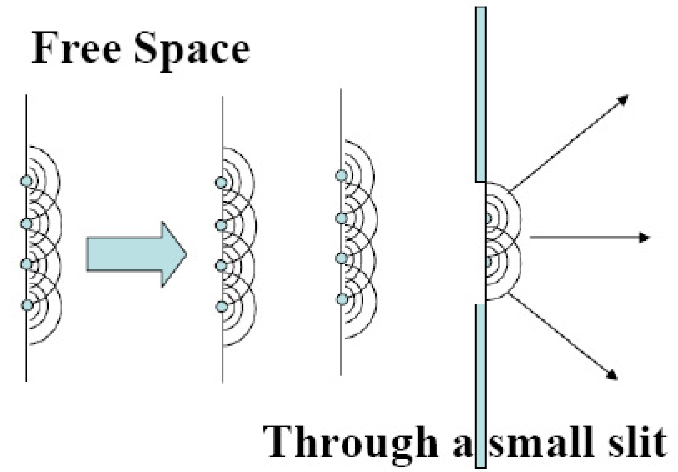


Diffraction

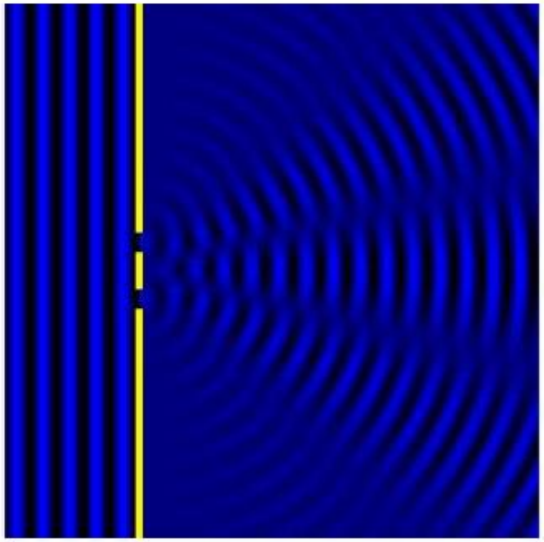
- Photolithography requires a system where the wavelength of light is comparable to the dimensions of the mask (effects of diffraction).
- Diffraction effects occur because light **dose not** travel in straight lines.
- The light pattern which **strikes** the **screen** (image plane) **covers** a **much larger area** than can be accounted for by simply drawing **straight lines** (ray tracing).This is very much like the situation we find in modern lithography where light passes though a mask with apertures with dimensions on the order of the light wavelength.

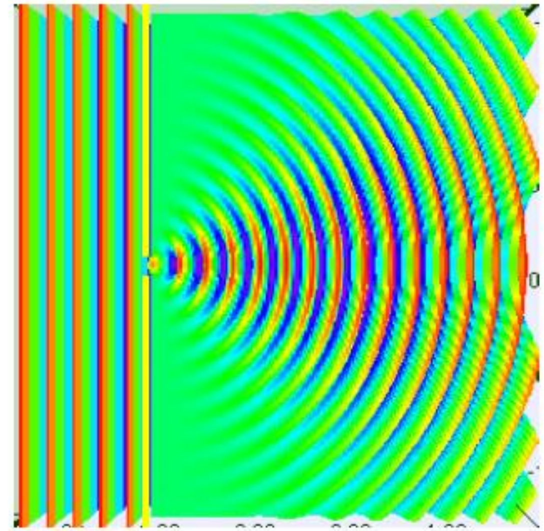


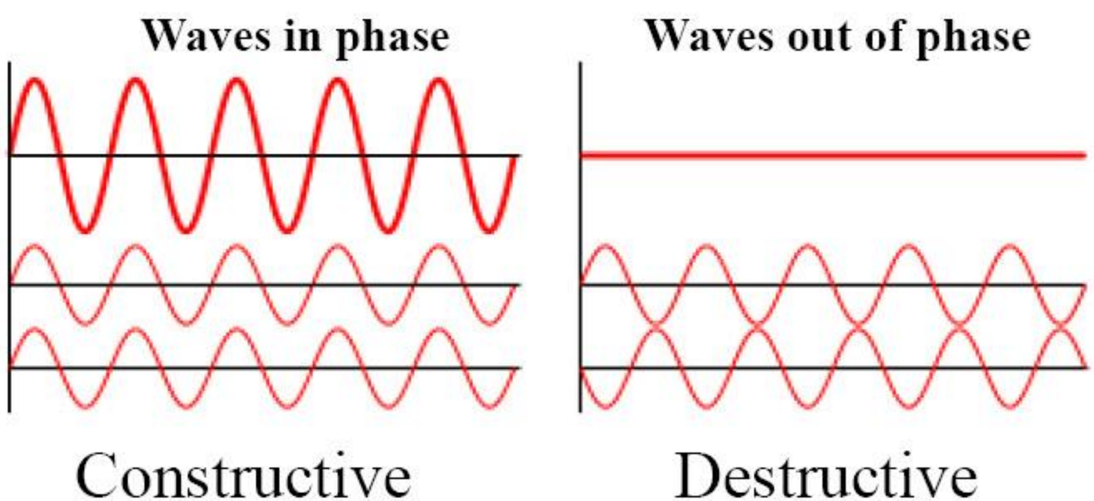
- **Huygens-Fresnel** principle states that every unobstructed point of a wave front at a given instant in time acts as a source of a spherical secondary wave let of the same frequency as the primary wave.



Wave Interference







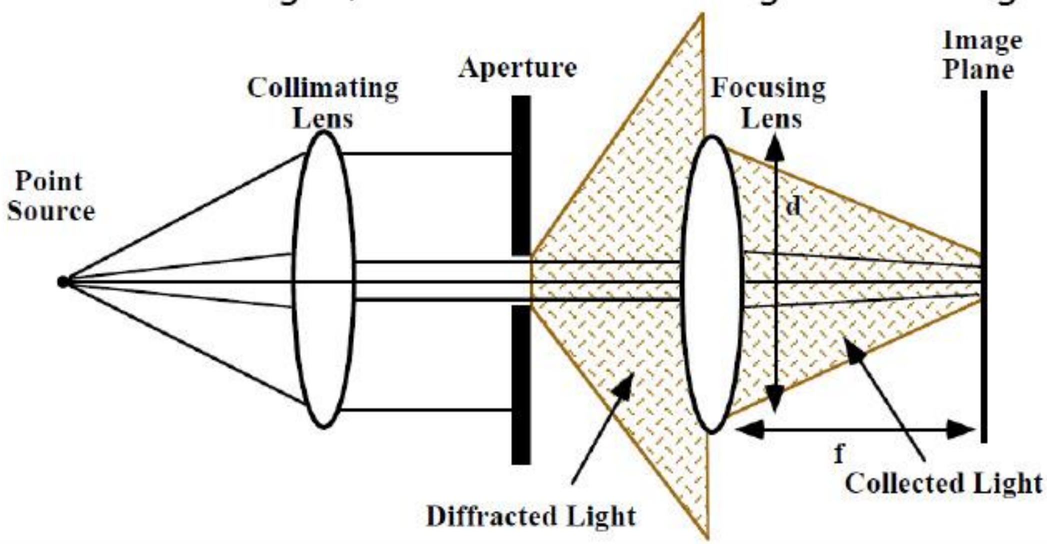
Diffraction

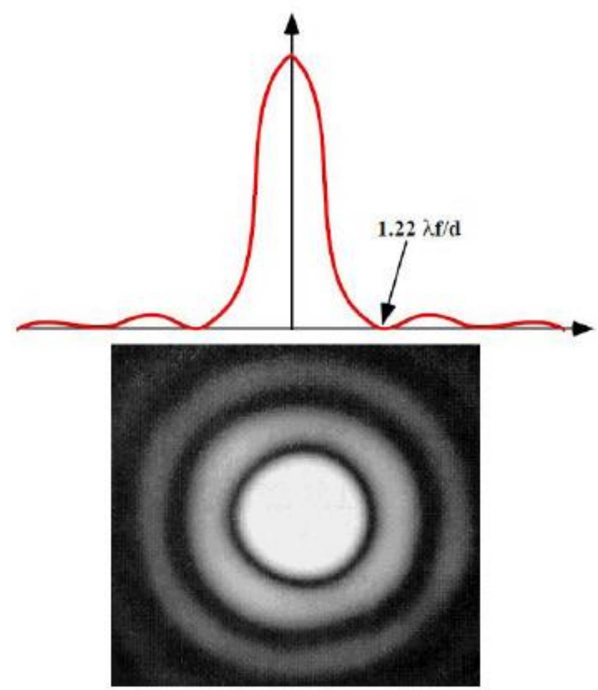
- The light "**bending**" that passes through the aperture carriers with it the information on the **size** and **shape** of that aperture.
- The **problem** is that this information because of the diffraction must all be collected to convey perfect information about the aperture to the wafer.
- The **focusing lens collects only part** of the **total diffraction pattern** passing through the aperture.
- The image intensity can be described mathematically by Bessel function

Diameter of central maximum $= \dfrac{1.22\lambda f}{d}$

d is the focusing lens diameter,

f is the focal length, and λ is the wavelength of the light





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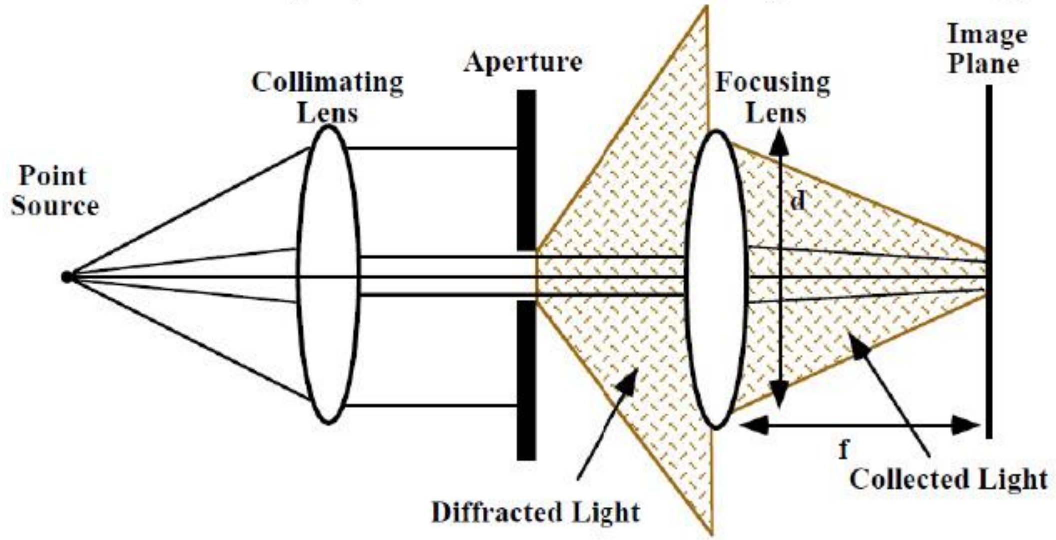
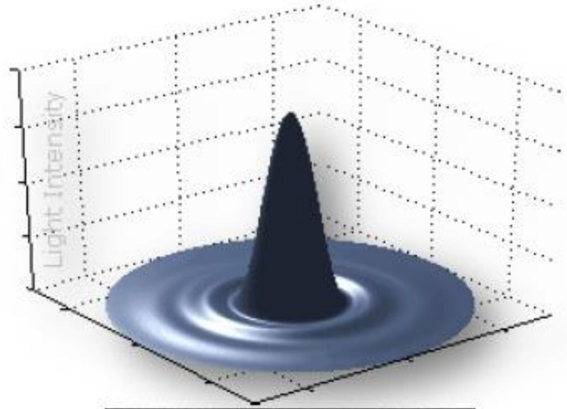
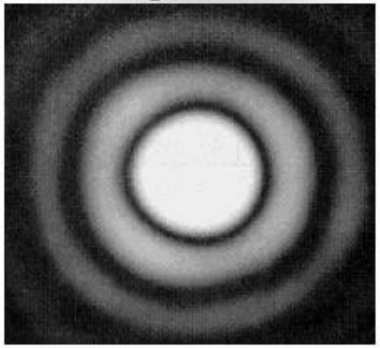
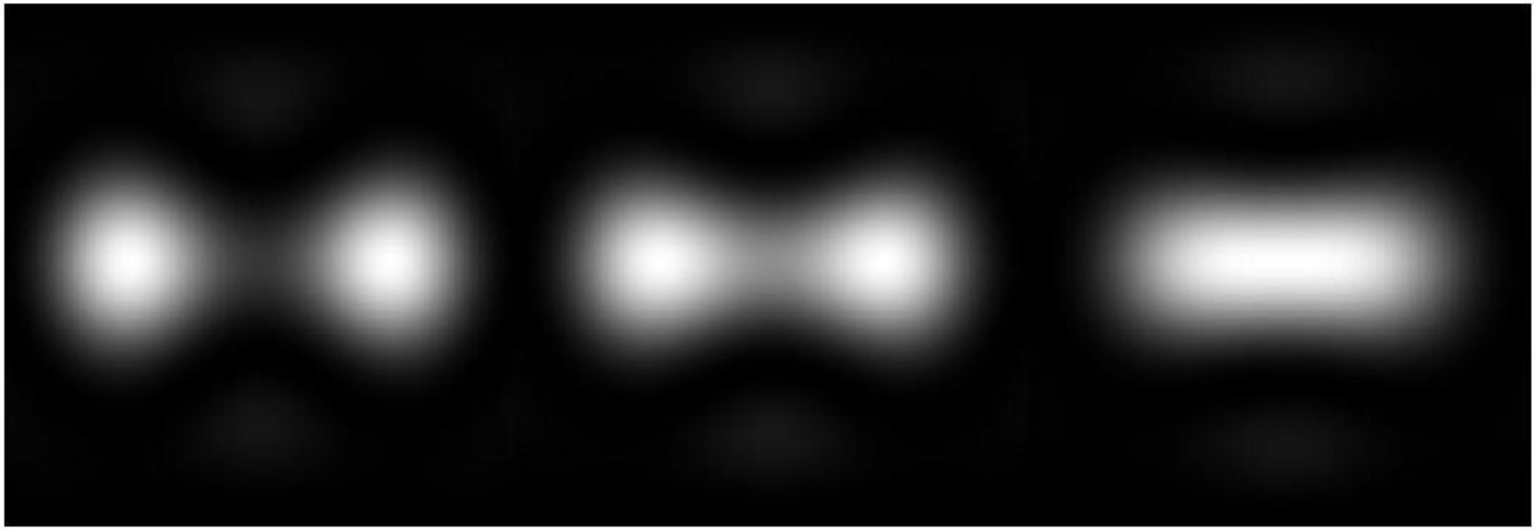


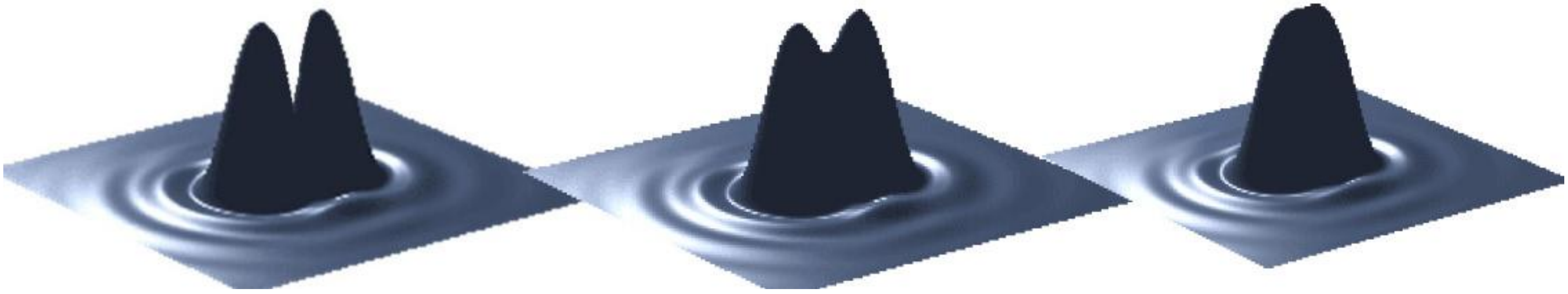




Resolution

Consider that we have two point source close together that we are trying to image. How close together can they be and still be resolved in the image plane?





Resolution

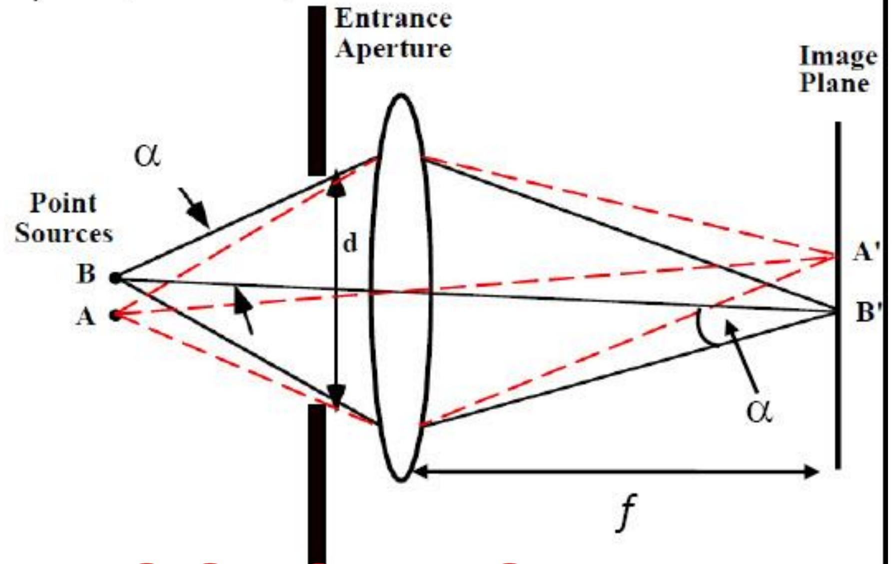
- Consider that we have two point source close together that we are trying to image. How close together can they be and still be resolved in the image plane?
- A reasonable criterion for resolution is that the central maximums of each point image lie at first minima of the adjacent point image. With this definition, the **resolution R** of the lens is given by

$$R = \frac{1.22\lambda f}{d} = \frac{1.22\lambda f}{n(2f\sin\alpha)} = \frac{0.61\lambda}{n\sin\alpha}$$

- Where n has been included for generality and is the index of refraction.
- The numerical aperture (NA) of the lens is by definition,

$$NA \equiv n\sin\alpha$$

$$\therefore R = \frac{0.61\lambda}{NA} = k_1\frac{\lambda}{NA}$$

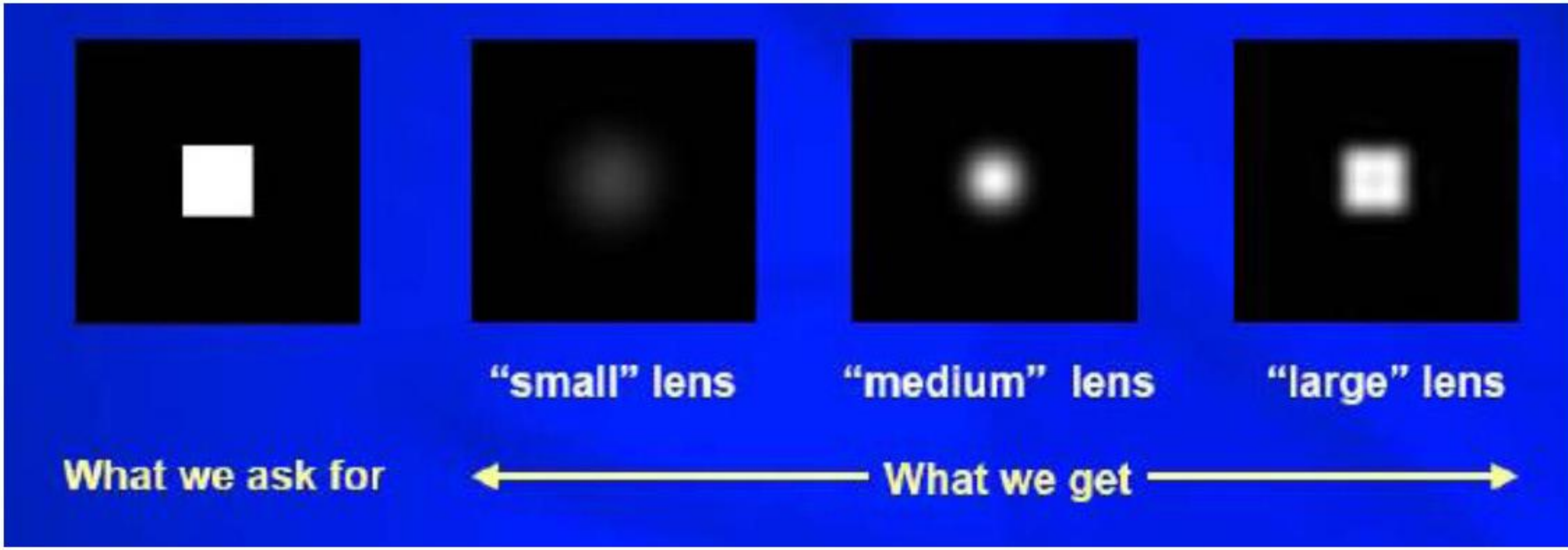


- **While resolution can be increased by:**
  - Decreasing λ
  - Increasing NA (bigger lenses)

NO PROOFS REQUIRED

Resolution

- Increasing NA (bigger lenses) Larger sin (α)



The **numerical aperture (NA)** of an optical system is a dimensionless number that characterizes the range of angles over which the system can accept or emit light.

Another way to increase the NA is Immersion (increasing n by using water instead of air)

Random Questions

- Two Random students to ask each other a question

  - Left side, first row, first one from the wall

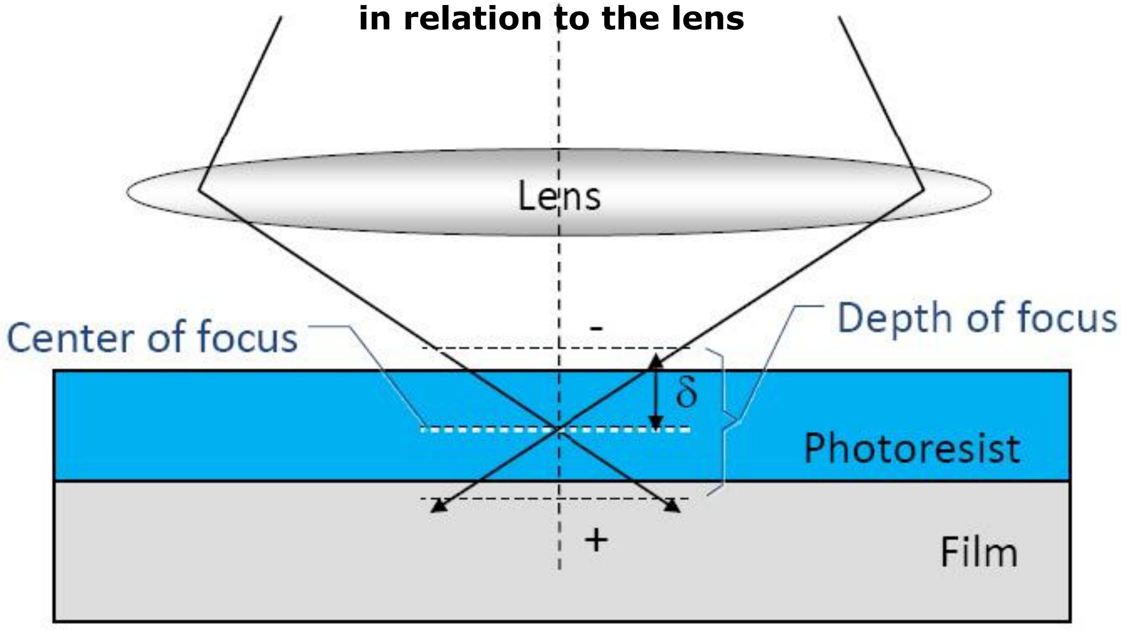
  - Right side, last row, second one from the wall

Depth of Focus

- However, higher NA lenses (very large lens/aperture) have a positive effect on the resolution but a negative effect on the depth of focus (DOF).
- The depth of focus is a (± δ) distance between its limits the image will appear to be in acceptably sharp focus.

$$DOF = \pm \frac{\lambda}{2(NA)^2} = \pm k_2 \frac{\lambda}{(NA)^2}$$

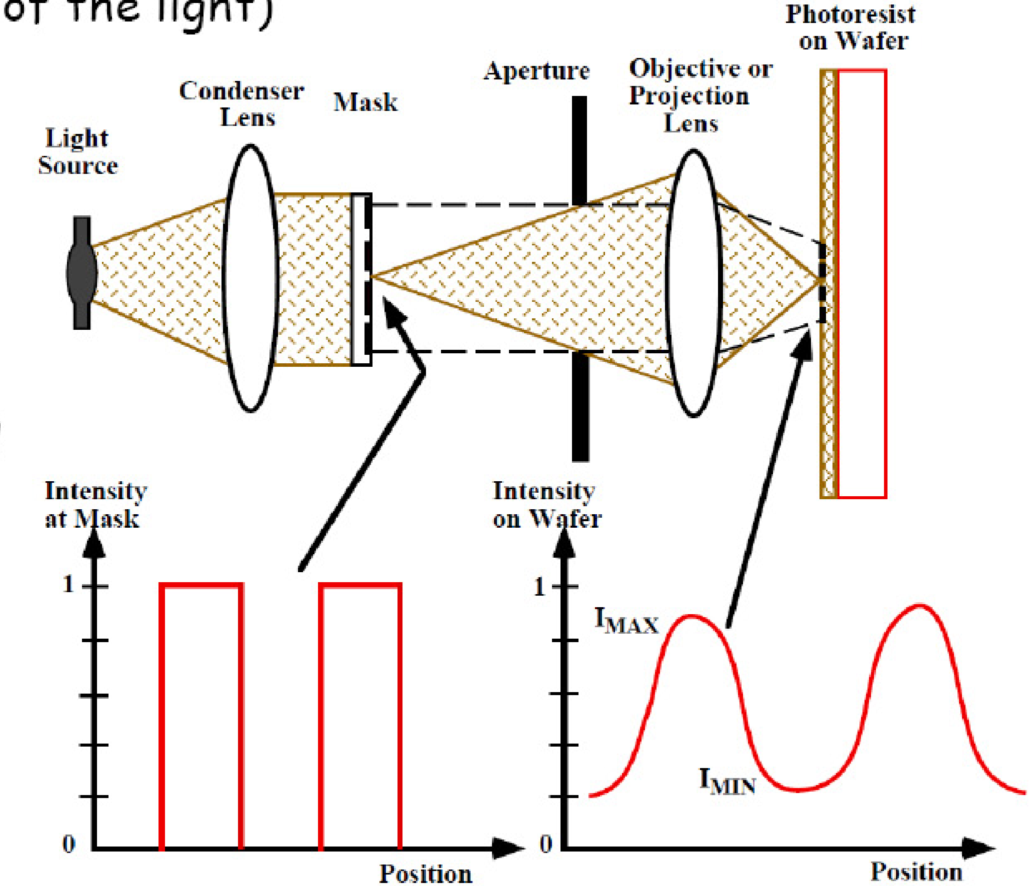
DOF measures the tolerance of placement of the image plane (the film plane in a camera) in relation to the lens



Modulation Transfer Function

- An additional basic concept regarding optical exposure systems is Modulation Transfer Function (MTF).
- MTF is a measure of the <u>**optical contrast**</u> in the image by the <u>**exposure system**</u>. The higher the MTF the better the optical contrast. MTF of an image can be defined as (where I is the intensity of the light)

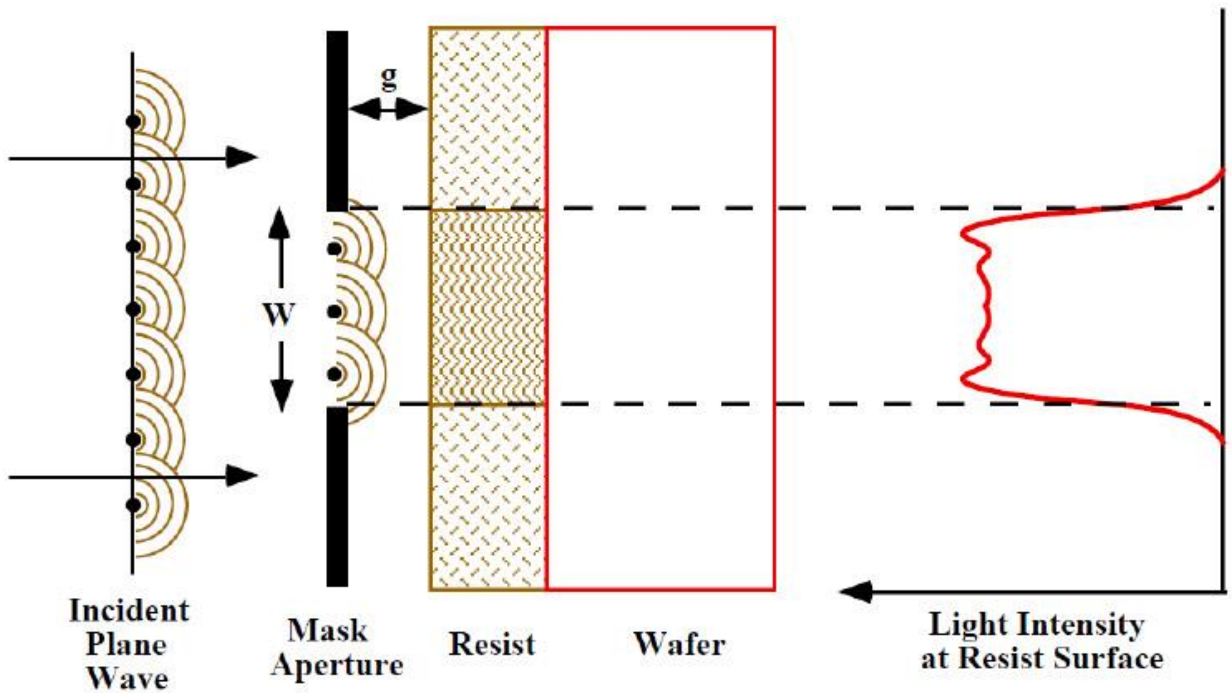
$$MTF = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}}$$



- MTF depends on the **feature size** also MTF increases with decreasing wavelength.
- MTF value of **≥0.5** is required in order to resolve the features.

Contact and Proximity Systems (Fresnel Diffraction)

- Contact printing systems operate in the near field or **Fresnel diffraction regime**.
- There is no lens between the mask and the resist on the wafer.
- The mask and the wafer are separated by small gap g (due to topography on the wafer surface)
- **As the separation g increases between the mask and resist, the quality of the image will degrade because diffraction effects will become more important.**



Contact and Proximity Systems (Fresnel Diffraction)

- The **image** can be calculated using **Fresnel diffraction theory** whenever the **gap g** falls within the limits

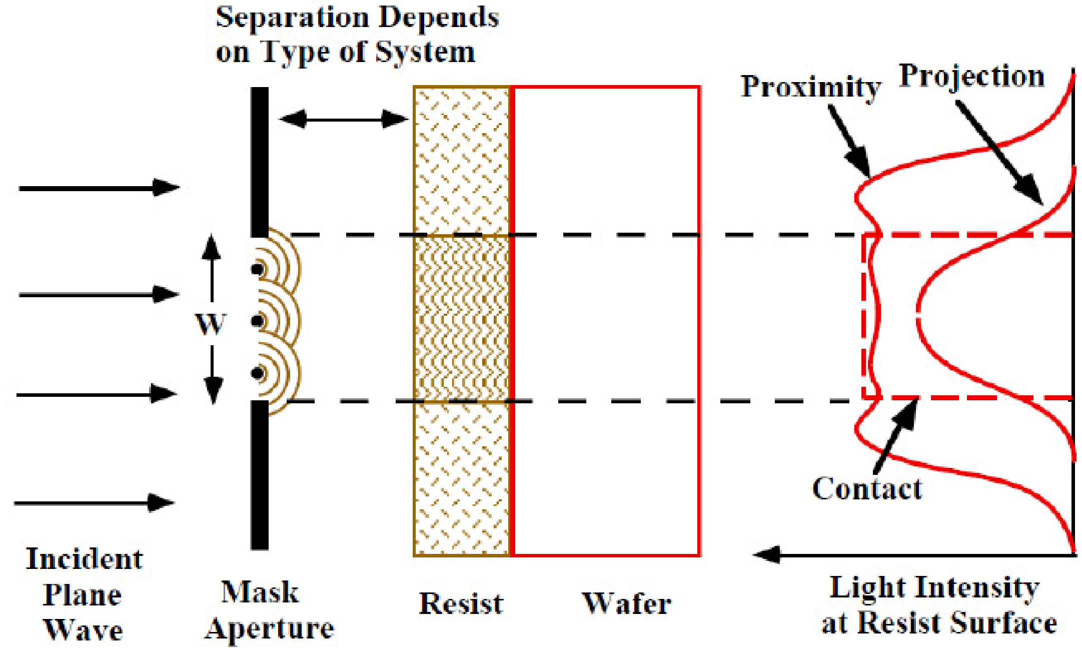
$$\lambda < g < \frac{W^2}{\lambda}$$

- **Within** the **Fresnel diffraction** range, **the minimum** resolvable **feature size** is on the order of

$$W_{min} \approx \sqrt{\lambda g}$$

- Thus if g = 10 μm and an i-line light source (λ = 365 nm) is used,

$$W_{min} \approx 2\ \mu m$$

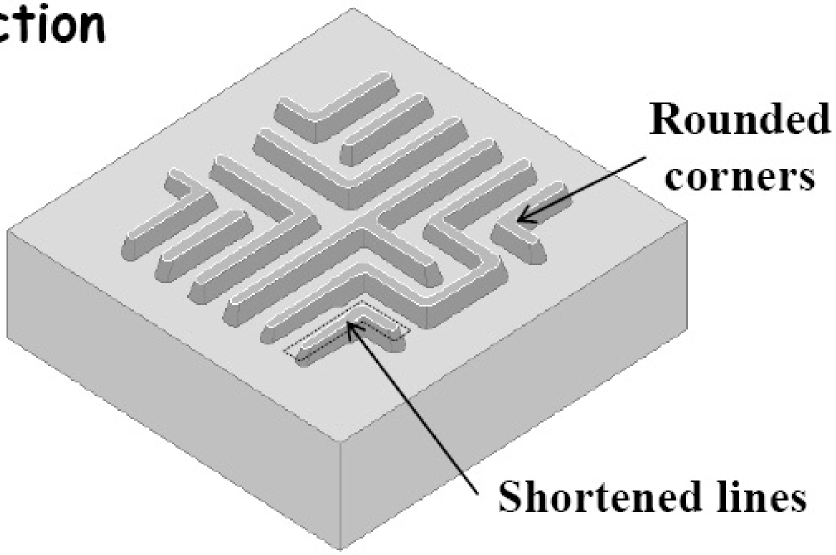


- **Hard Contact** → very high resolution
- **Proximity** → degrades Fresnel diffraction
- **Projection** → Diffraction is produced

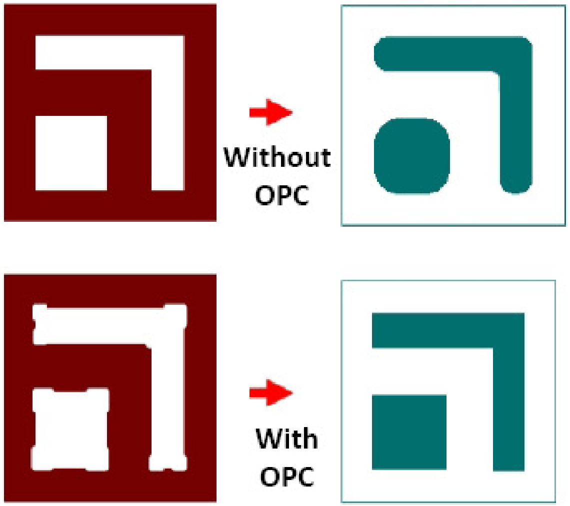
Summary of wafer printing systems

Mask Engineering
Optical Proximity Correction

- Sharp features are lost due to diffraction
  - Rounded corners rather than square
  - Changes in line width between isolated and grouped lines
  - Shortening of the ends of narrow linear features.

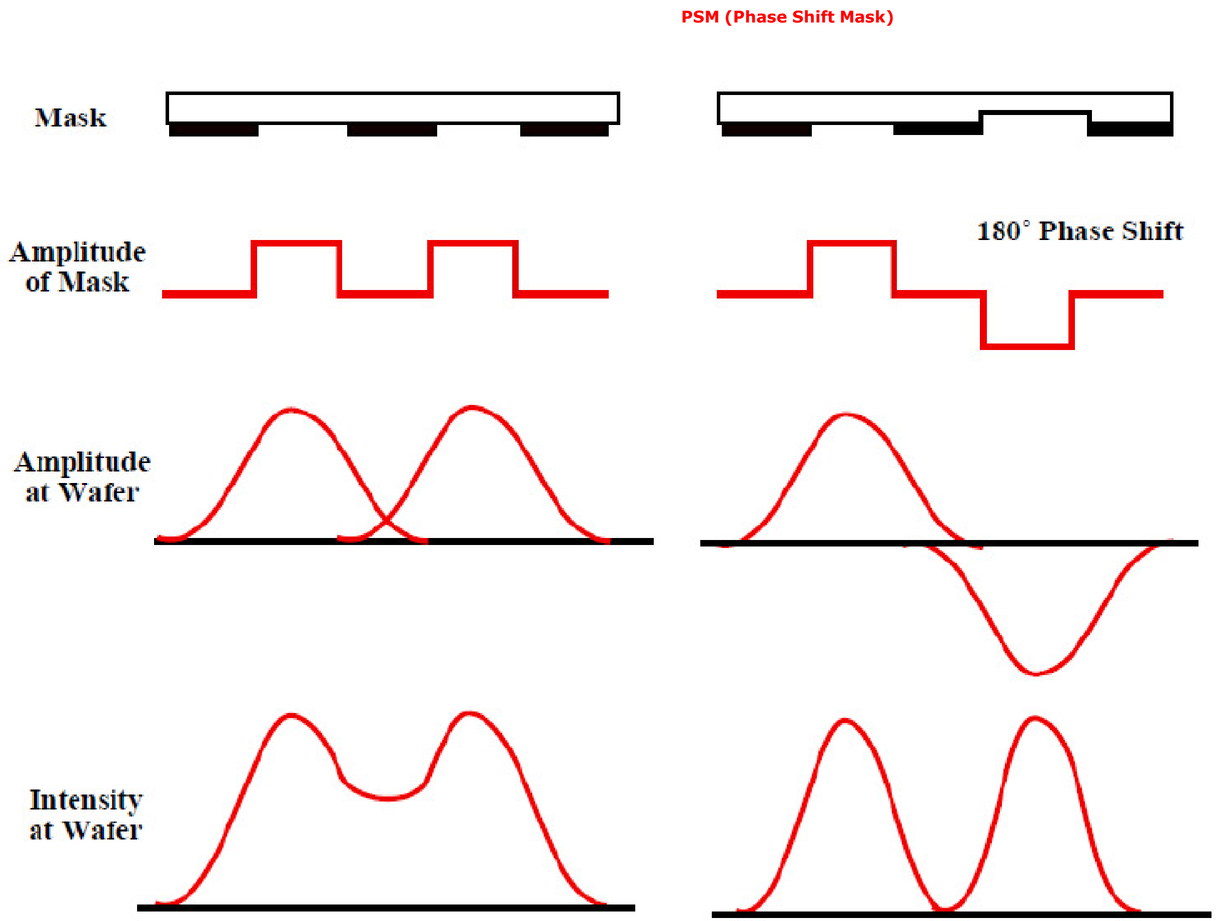


- Optical Proximity Correction (OPC) can be used to calculate and compensate somewhat for diffraction effects.
  - By adjusting the feature dimensions and shapes on the mask.
  - This could be done through software.



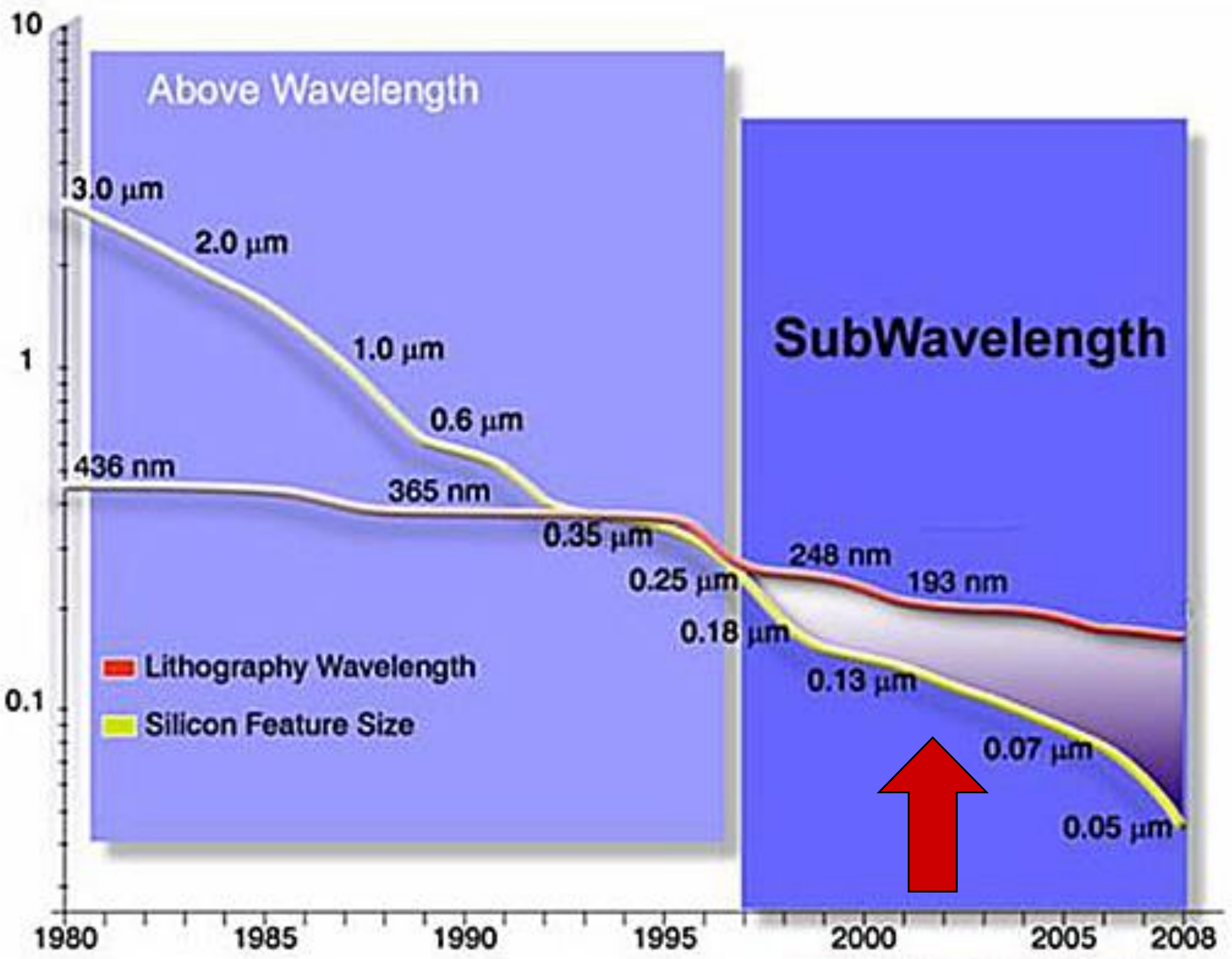
Mask Engineering
Optical Phase Shifting

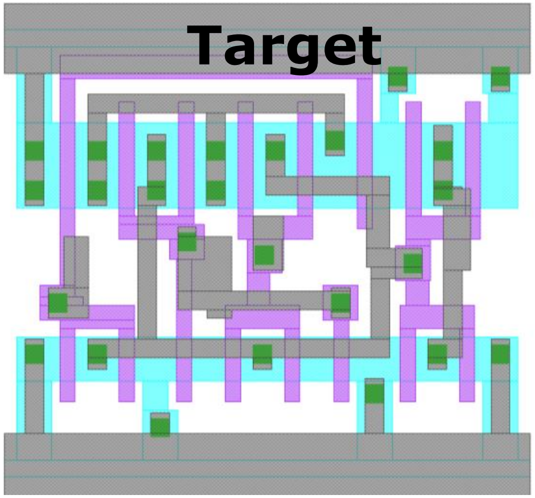
- Another approach uses phase shifting techniques to improve the resolution of the printed images.

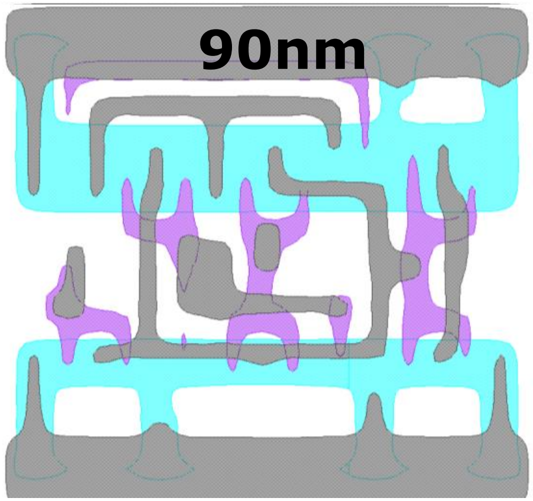


- Such phase shifting techniques can either be used to improve the quality of the image or to improve the depth of focus of the exposure system at a constant resolution by using a lower NA system.

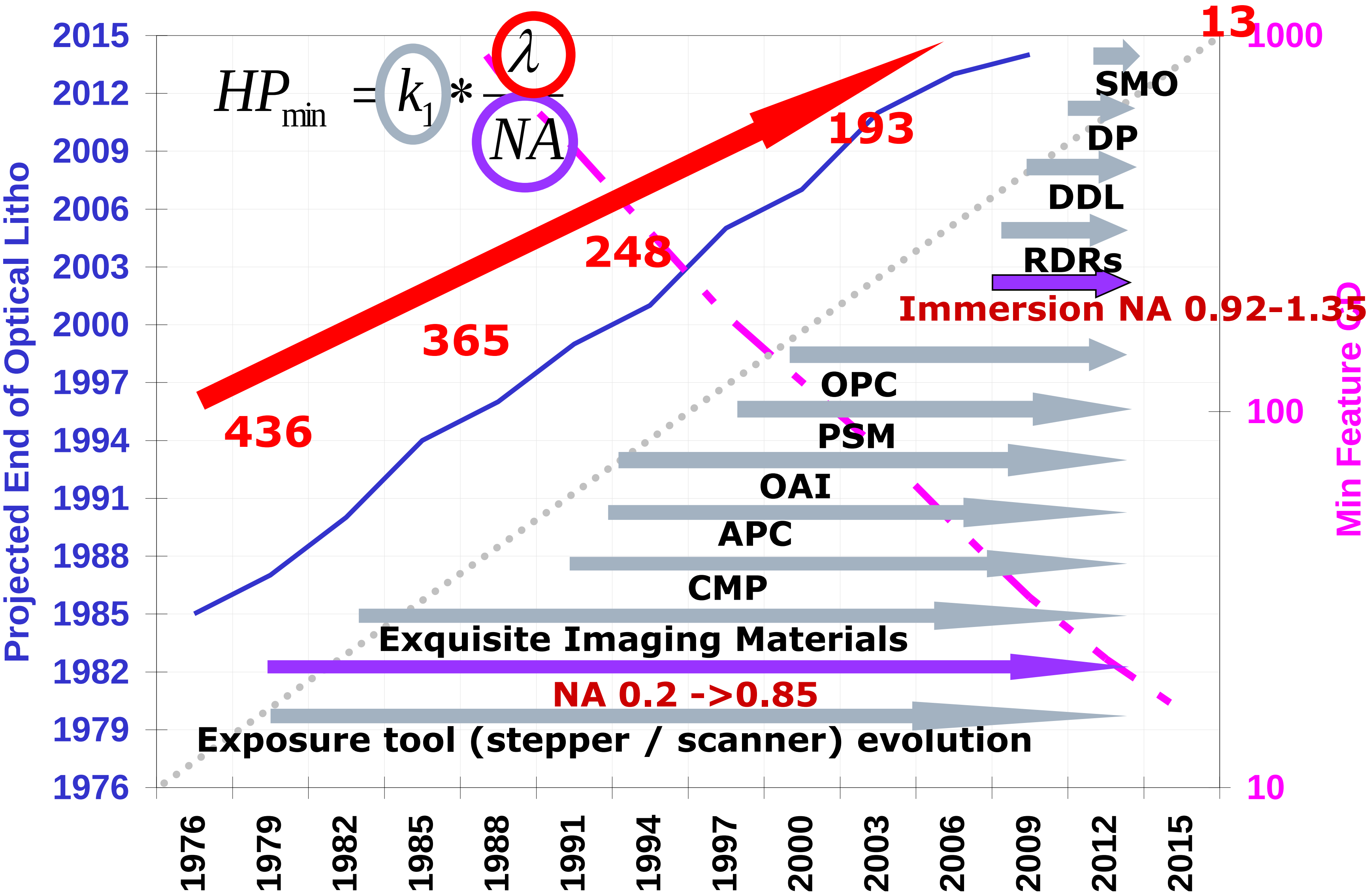
Challenge – Sub Wavelength Features







The End of Optical Lithography?



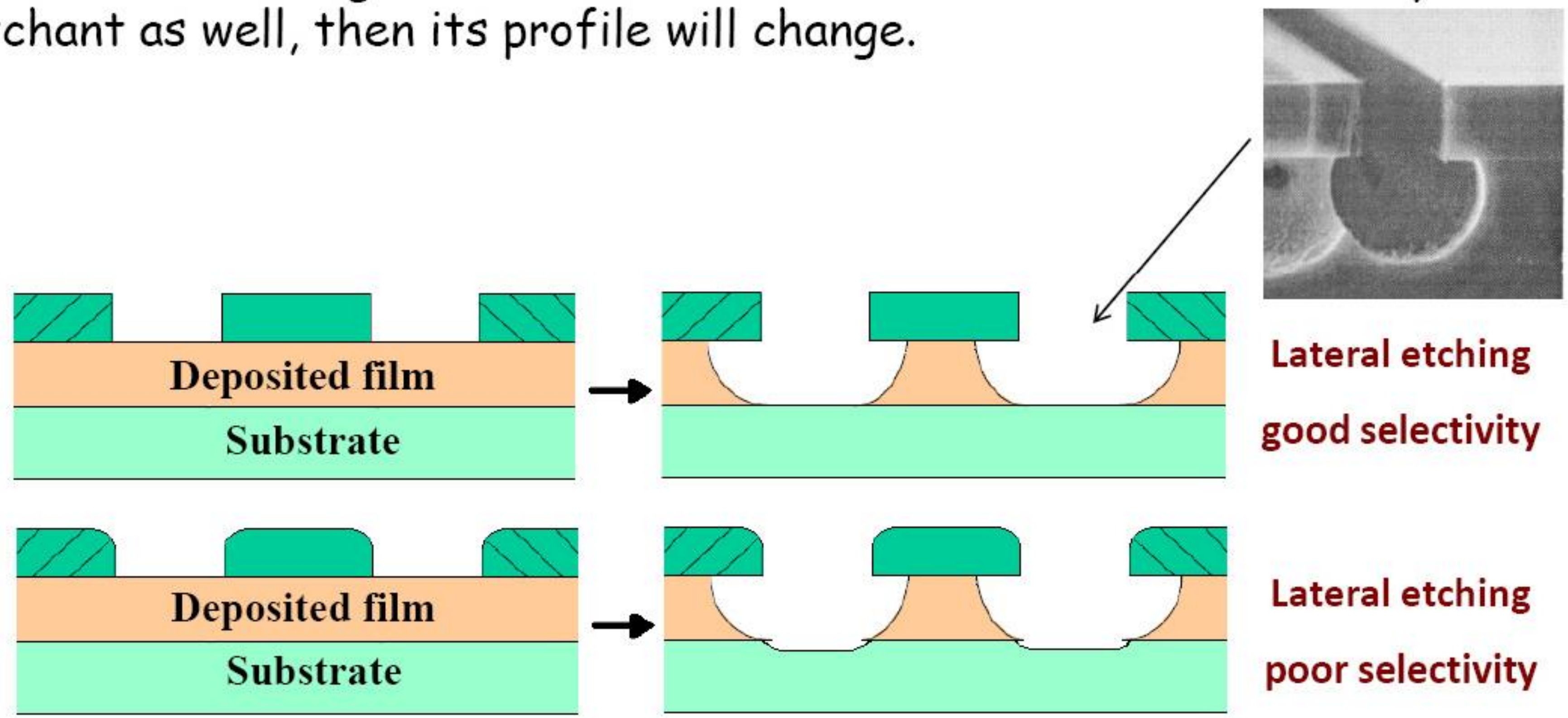
Dry Etching versus Wet Etching

- Wet Etching
  - Isotopic
  - Good Selective

- Dry Etching <Plasma>
  - Anisotropic (Vertical)
  - Poor Selective

Non-idealities of Etch Profiles

- In reality the etching is both **vertical** and **lateral**. This leads to undercutting of the photoresist mask and nonvertical sidewalls in the film.
- If the **photoresist** is **not perfectly rectangular**, with rounded **top corners** and **sloped sides**, this leads to **more lateral etching** of the film since the photoresist mask get narrower and if the substrate is attacked by the etchant as well, then its profile will change.

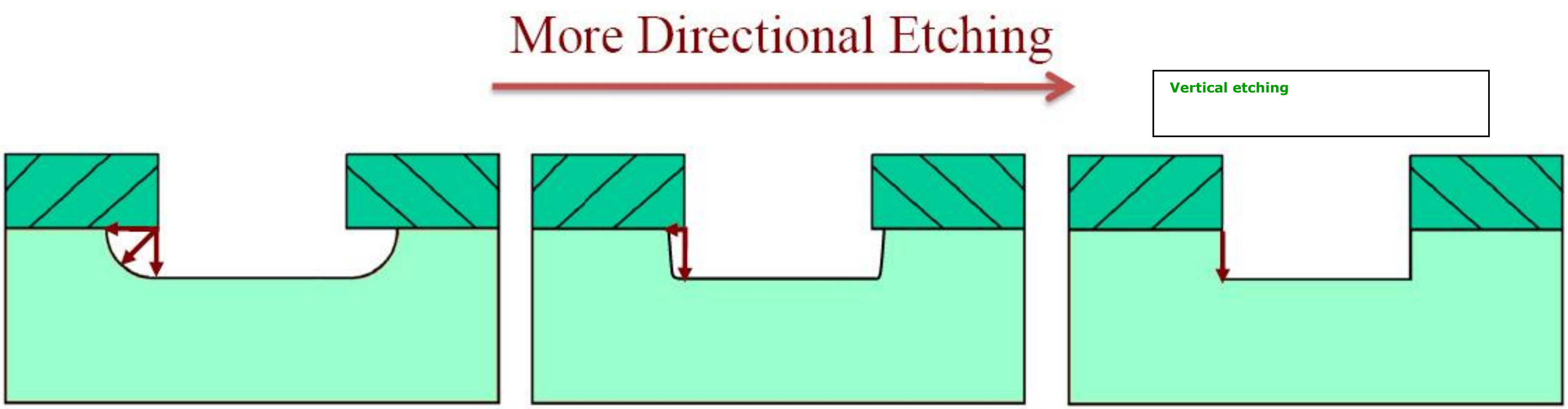


Lateral etching
good selectivity

Lateral etching
poor selectivity

Etch Degrees of Anisotropic

- **Isotropic etching:** occurs when etch **rates** are the **same in all directions**. The etch distance laterally under each side of the mask is the same as vertically under the mask opening.
- **Anisotropic etching:** when **less etching occurs laterally**.
- **Completely anisotropic etching:** when **no etching at all occurs in the lateral direction**.



Isotropic — Anisotropic — Completely Anisotropic

Best to use with large features

Best for making small features with vertical sidewalls

Wet Etching

- The **first etchants** used in the **integrated circuit industry** were simple **wet chemical etchants**. Wet etches were developed for **all steps** in the **fabrication process**.
  - A common wet **etch for SiO_2** is **hydrofluoric acid**, **HF**. The overall reaction is

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$$

- Wet etchants work by **chemically reacting** with the film to form **water-soluble** byproducts or **gases**, such as H_2SiF_6 **byproduct** which is a **water-soluble complex**.

- The common **etchant for silicon** is a mixture of **nitric acid (HNO_3) and HF**. The **nitric acid** partially **decomposes to nitrogen dioxide**, NO_2, which then **oxidizes the surface** of the silicon by the reaction

$$Si + 2NO_2 + 2H_2O \rightarrow SiO_2 + H_2 + 2HNO_2$$

The overall reaction is

$$Si + HNO_3 + 6HF \rightarrow H_2SiF_6 + HNO_2 + H_2O + H_2$$

Random Questions

- Two Random students to ask each other a question

- Left side, third row, fourth one from the wall

- Right side, fifth row, last one from the asile

  - Punishment:

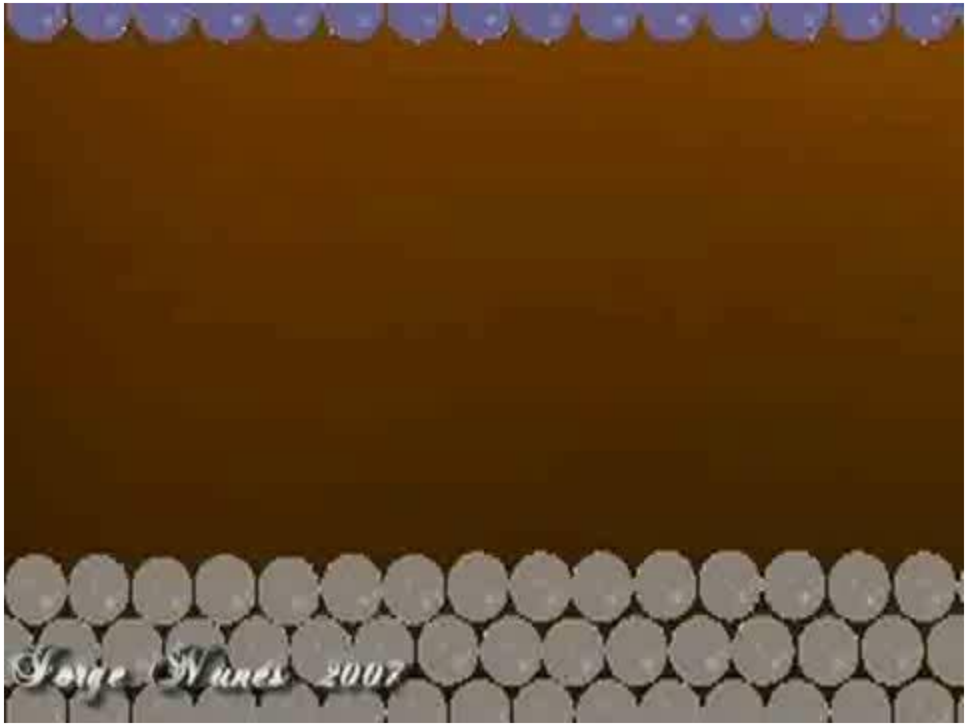
Write from 1 to 20 on the board in less than 10 seconds. Repeat till success

Basic Deposition Tools

- Physical Vapor Deposition (PVD)
  - includes Sputtering and Evaporization
- Sputtering deposition
  - **In sputter deposition, a target made of a material to be deposited is physically bombarded by a flux of inert-gas ions (usually Argon due to its heavy atoms) in a vacuum chamber**
  - **Atoms or molecules from the target are ejected and deposited onto the wafer**

Basic Deposition Tools

- Sputtering deposition
  - **DC sputtering used only for conductive materials..WHY?**
  - **RF sputtering can be used for both conductive and non-conductive**
  - **RF sputtering uses 13.56MHz…WHY?**

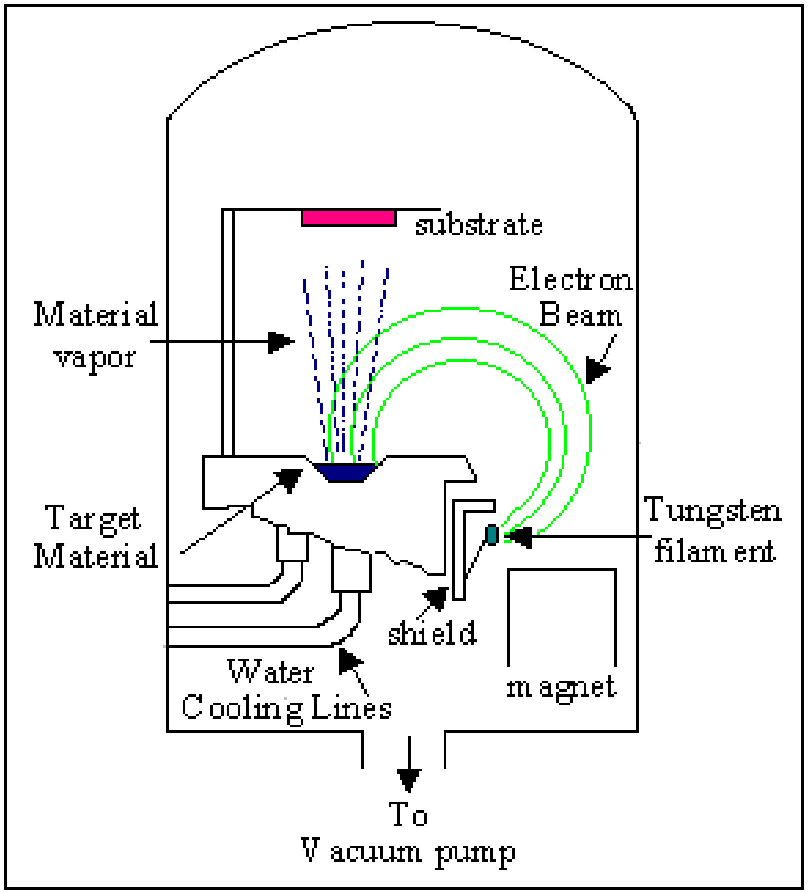


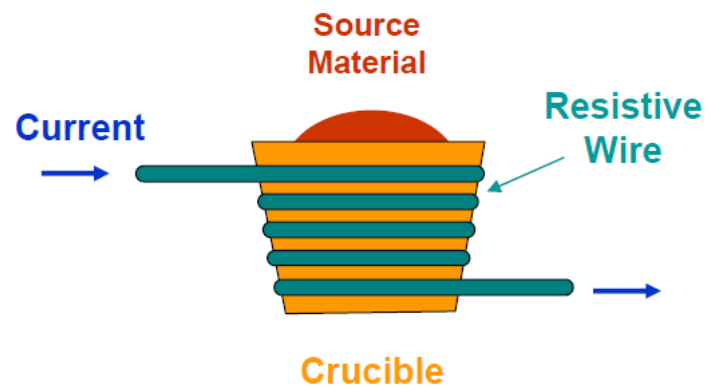
Basic Deposition Tools

- **Evaporization**
  - Evaporation involves the heating of a source material to a high temperature, generating a vapor that condenses on a substrate to form a film
  - Evaporation is performed in a high vacuum chamber
  - Target heating can be done
    - resistively by passing an electrical current through a tungsten filament, strip, or boat holding the desired material
    - high voltage (i.e., 10-kV) electron beam (e-beam) over the source material
    - E-beam is provide better-quality films and slightly higher deposition rates (5–100 nm/min), but the deposition system is more complex than the resistive heating

Basic Processing Tools

- Evaporization





Basic Deposition Tools

- **Spin-On Methods**
  - Spin-on is a process to put down layers of dielectric insulators and organic materials
  - Unlike the methods described earlier, the equipment is simple, requiring a variable-speed spinning table with appropriate safety screens
  - A nozzle dispenses the material as a liquid solution in the center of the wafer. Spinning the substrate at speeds of 500 to 5,000 rpm for 30 to 60 seconds spreads the material to a uniform thickness
  - Photoresists are common organic materials that can be spun on a wafer with thicknesses between 0.5 and 20 μm

Basic Deposition Tools

- **Spin-On Methods**

Random Questions

- Two Random students to ask each other a question

- Left side, second row, third one from the wall

- Middle column, third row, fourth one from the left

  - Punishment:

Write from 1 to 30 on the board in less than 10 seconds. Repeat till success

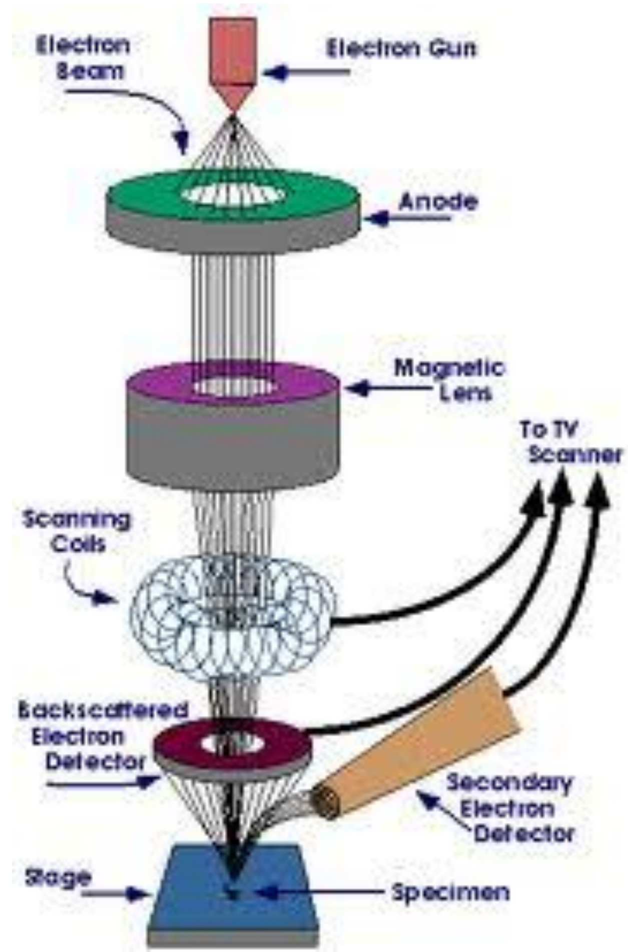
Nano Investigating Tools

- Optical microscopes are limited to 200nm due to light diffraction and resolution limits
- New Nano investigation tools are utilized such as:
  - SEM
  - TEM
  - AEM
  - SPM
  - STM
  - AFM
  - Nano-Lithography

Scanning Electron Microscope (SEM)

- **SEM uses a focused beam of electrons to scan the surface of the sample in Vacuum environment inside the SEM**
- **SEM samples must conduct electricity**
- **a beam of electrons of high energy down through a series of magnetic lenses, which focus the beam to a very fine point**
- **A set of scanning coils move the focused beam back and forth across the specimen row by row**
- **As the electron beam hits each spot on the sample, electrons are reflected to a detector that counts these electrons and sends the signals to an amplifier**
- **The final image is collected from the number of electrons emitted from each sample spot and shown on a computer screen**

Scanning Electron Microscope (SEM)

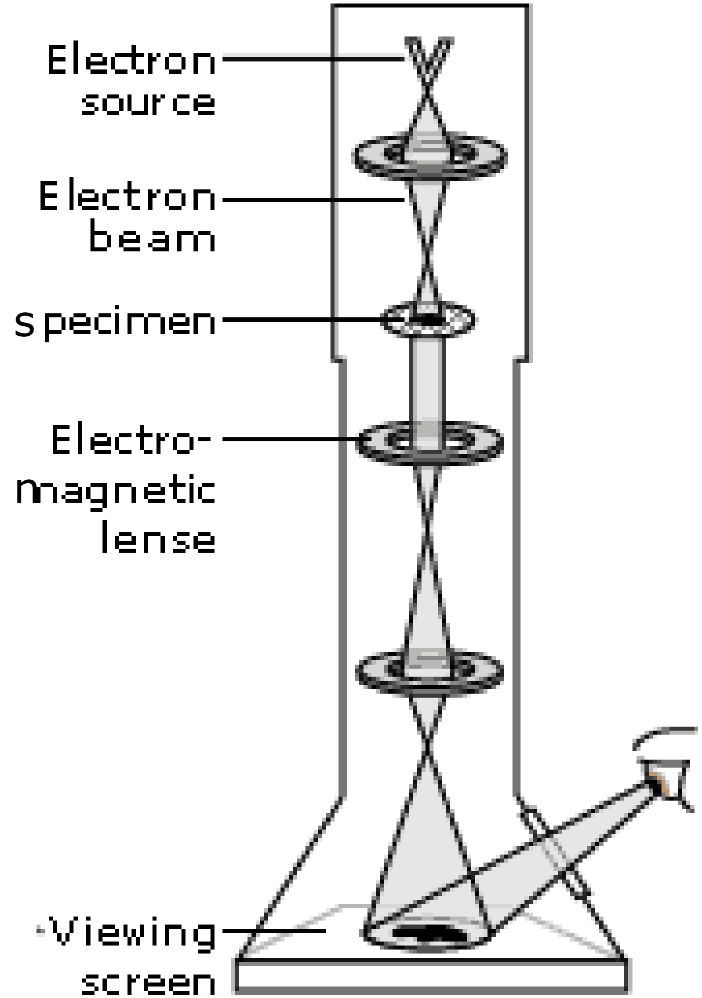


Transmission Electron Microscope (TEM)

- **SEM can only scan the surface of the sample, whereas, TEM can see all the way through a sample**
- **SEM provides 3D images whereas TEM provides 2D images with more details.**
- **A wide beam of electrons passes through a thinly sliced sample to form an image**
- **The electrons that a TEM uses to project images are focused by magnets similar to the glass lens bends light in a regular optical microscope**
- **Electrons can be focused until a clear picture appears on the monitor**
- **TEM is similar to a regular optical microscope in that thicker or denser areas of a sample absorb or scatter the beam causing dark areas, while less dense areas look bright**

Transmission Electron Microscope (TEM)

- At the bottom of the microscope the unscattered/unabsorbed electrons hit a fluorescent screen, which gives rise to a "shadow image" of the specimen with its different parts displayed in varied darkness according to their density
- The image can be photographed with a camera
- Resolution of a TEM is about 0.1nm to 0.2nm



Analytical Electron Microscope (AEM)

- TEMs are used to look inside materials at high magnification
- To expand the role of TEM, We need to develop the ability to measure material structure and chemical characteristics atom by atom
- For this purpose, a TEM is equipped with analytical instruments, such as X rays and electron spectrometers, which makes TEM an analytical electron microscope (AEM)
- These machines measure and form images from X rays created by atoms
- Such measurements can distinguish, for example, between carbon atoms from nitrogen atoms, allowing scientists to map out the compositions of materials

Random Questions

- Two Random students to ask each other a question

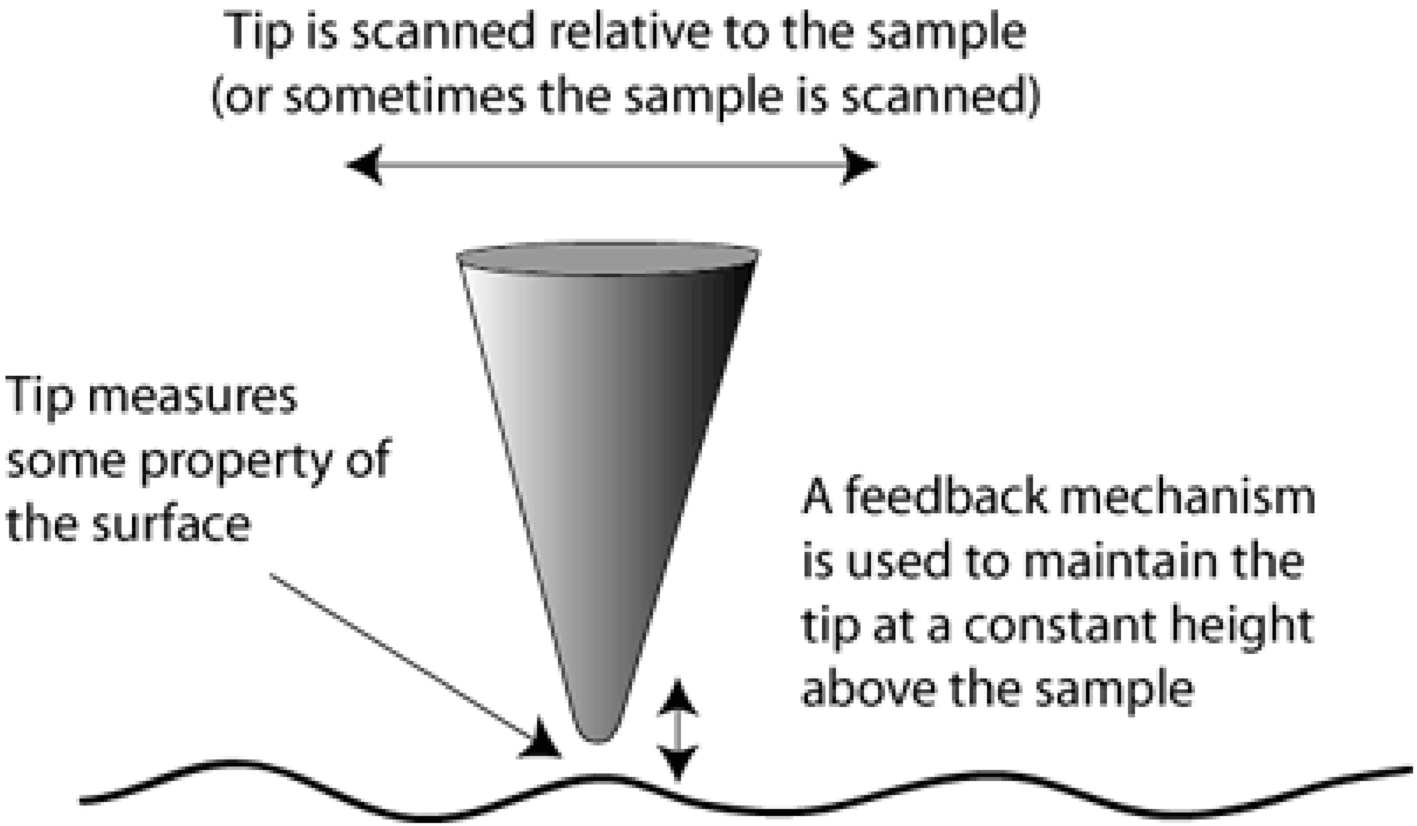
- Middle column, fifth row, second one from the wall
- Right side, first row, fourth one from the wall
- Punishment:

Tell the birthday of 3 other colleagues

Scanning Probe Microscope (SPM)

- It is used to study the surface characteristics of material at the atomic scale
- It has a probe tip that tracks and records sample surface changes as the surface of the sample is moved
- The tip records the height, electrical or other changes on the surface
- SPM methods are used to form and investigate tiny circuit elements and custom made molecules
- Two types:
  - Scanning tunneling microscope (STM)
  - Atomic force microscope (AFM)

Scanning Probe Microscope (SPM)

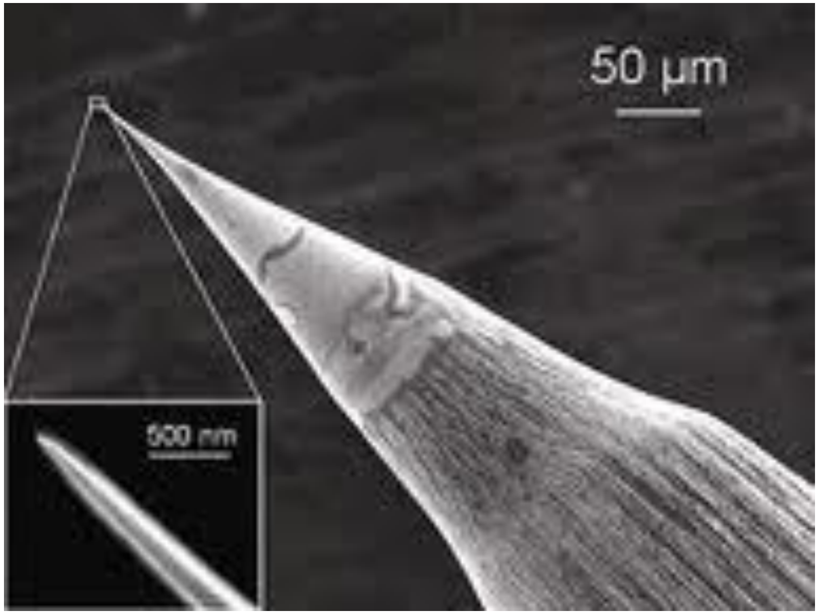


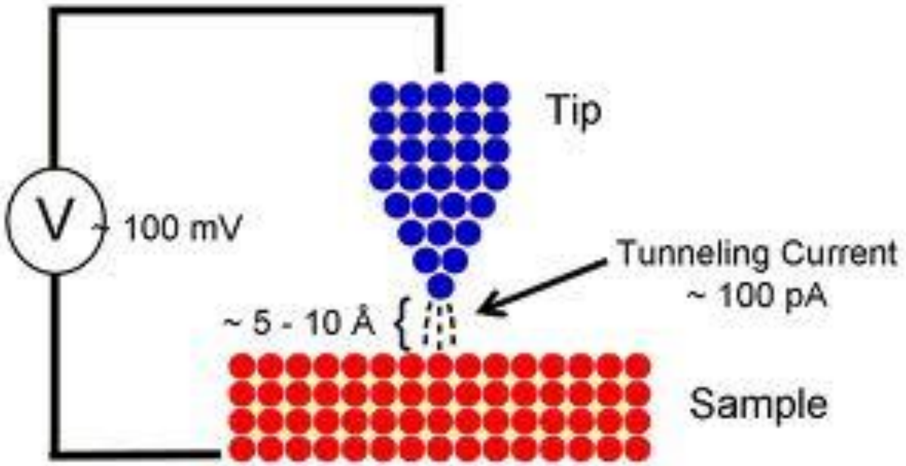
Scanning Tunneling Microscope (STM)

- This microscope uses a fixed probe tip to measure material's surface electrical characteristics
- Various kinds of images can be seen depending on the type of STM probe tip used
- The simplest method is to scan the structure of a surface keeping the tip a constant distance away such as 0.2 nm, and the tip is raised or lowered to keep the current flowing at a constant value, which means the distance is maintained
- a voltage is created between the probe tip and the conductive sample's surface to cause a flow of electrons across the gap
- When the tip moves up or down relative to the surface to keep the tunneling current constant, it then tracks and records the sample's topography

Scanning Tunneling Microscope (STM)

- For current to be maintained the sample must be conductive (i.e., Insulating sample must be coated first by a conductive coating)
- STM can also cause chemical reactions and create ions by pulling off individual electrons from atoms or adding these electrons

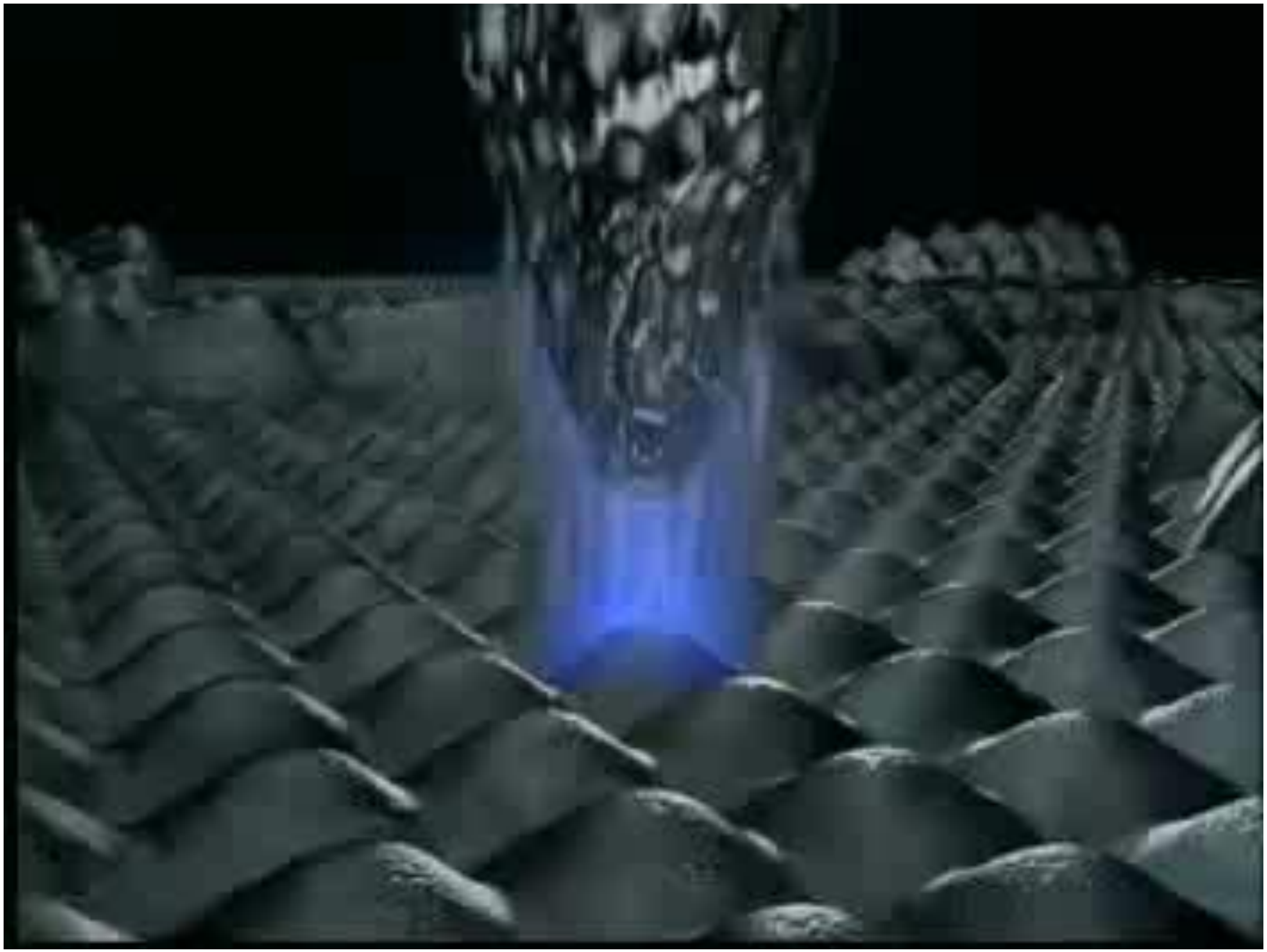




Scanning Tunneling Microscope (STM)

- The up and down motions of the tip are controlled by piezoelectric elements and recorded by a computer
- Piezoelectricity is the ability of some crystals to create mechanical stress, or motion in response to applying voltage
- the piezoelectric crystal expands or contracts to keep the distance between the tip and sample surface constant depending on the voltage applied to it

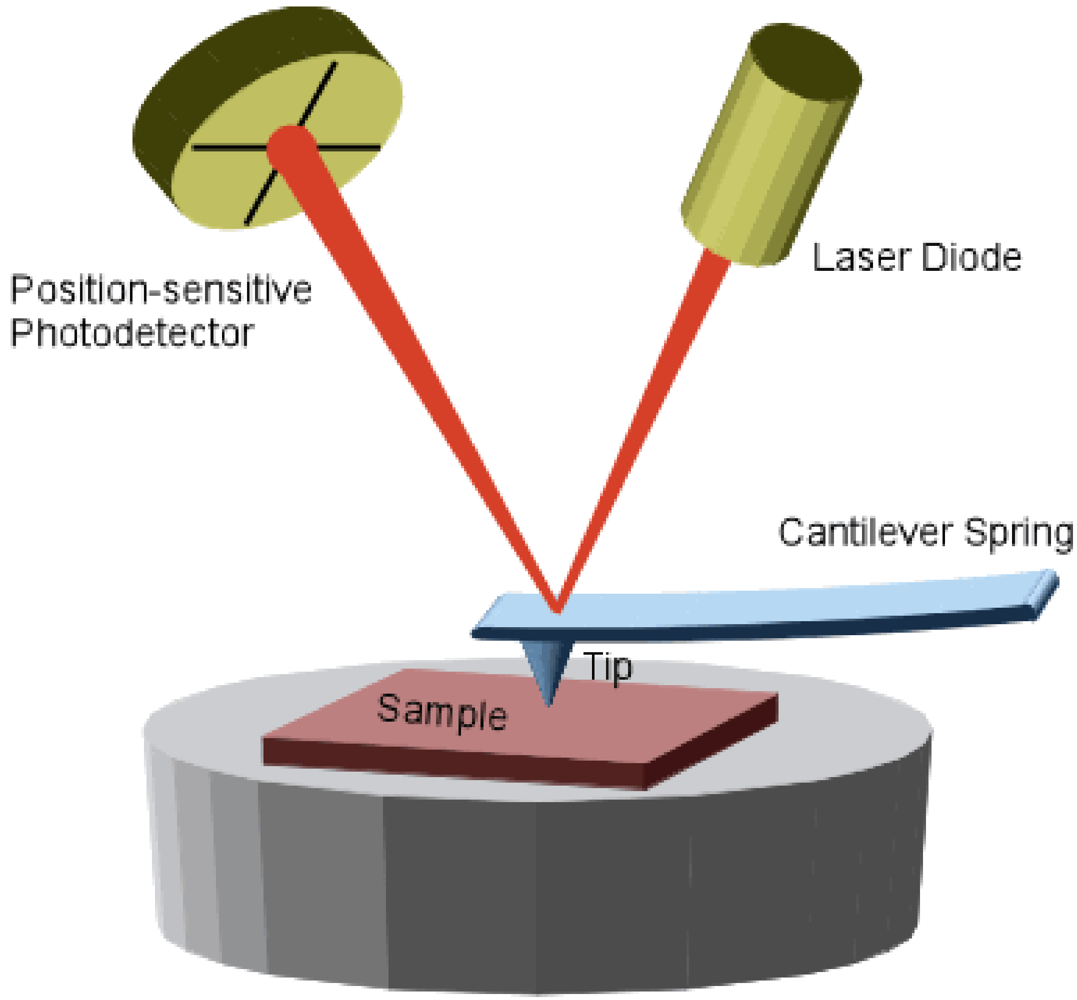
Scanning Tunneling Microscope (STM)



Atomic Force Microscope (AFM)

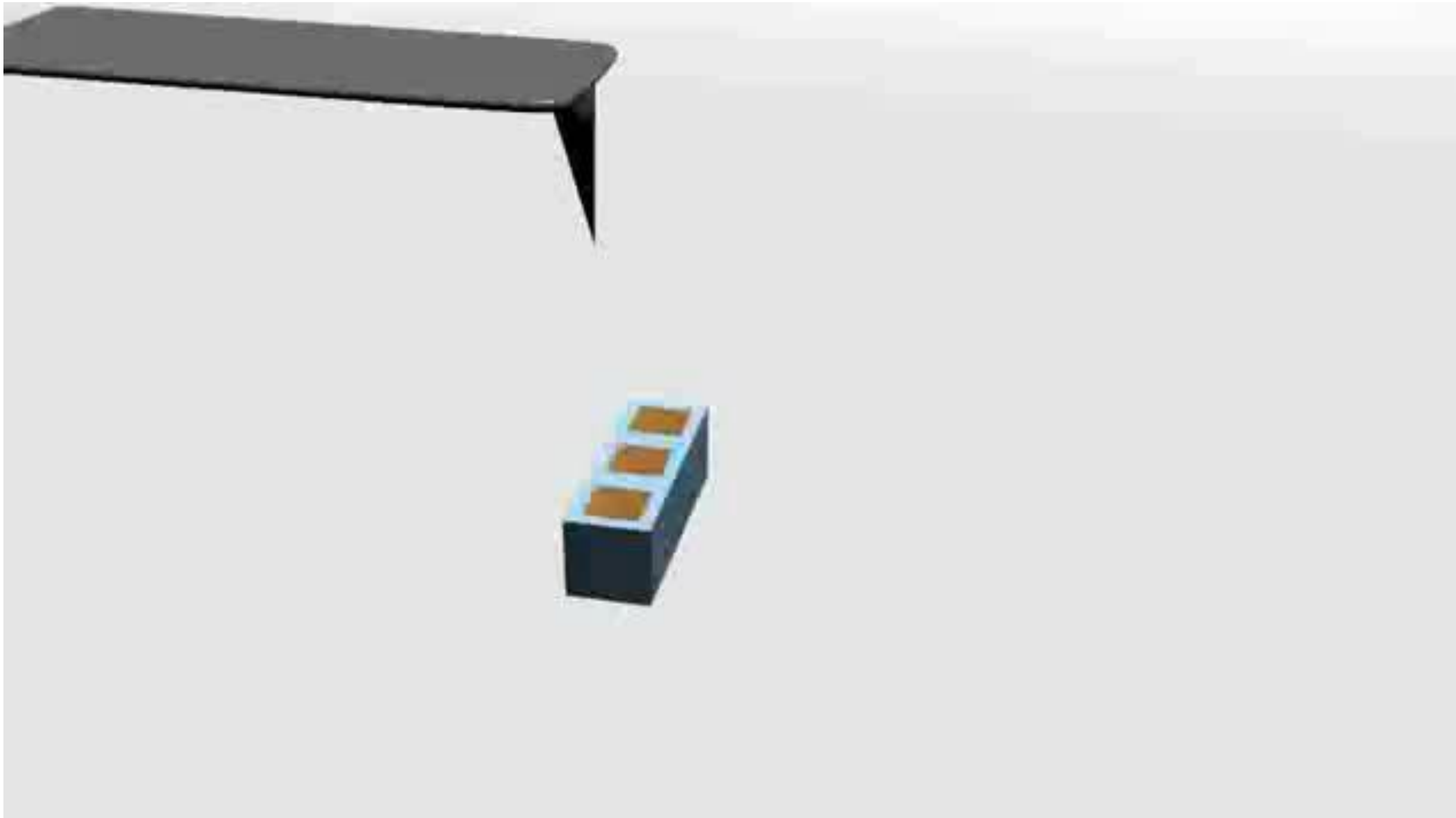
- **An important limitation of STM is that is can be used only with specimens that conduct electric current**
- **Atomic force microscopes (AFMs) can be used to study conducting and insulating materials**
- **AFM is based on scanning a flexible force sensing cantilever across a specimen**
- **Attractive and repulsive forces acting on the cantilever cause deflections that can be measured with laser methods, in which a laser beam reflects off the back side of the probe tip to find the position of the probe tip**

Atomic Force Microscope (AFM)



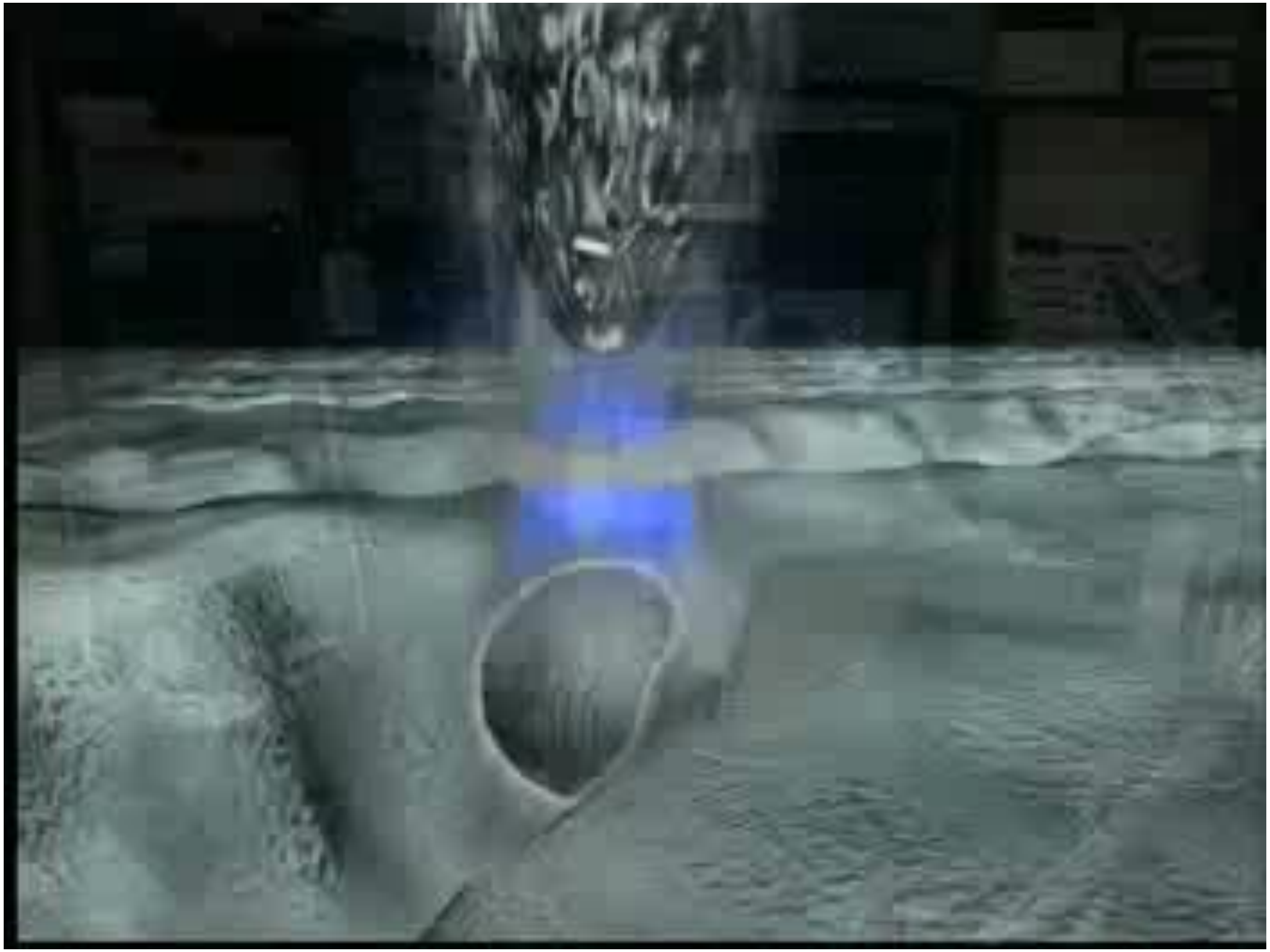
Atomic Force Microscope (AFM)

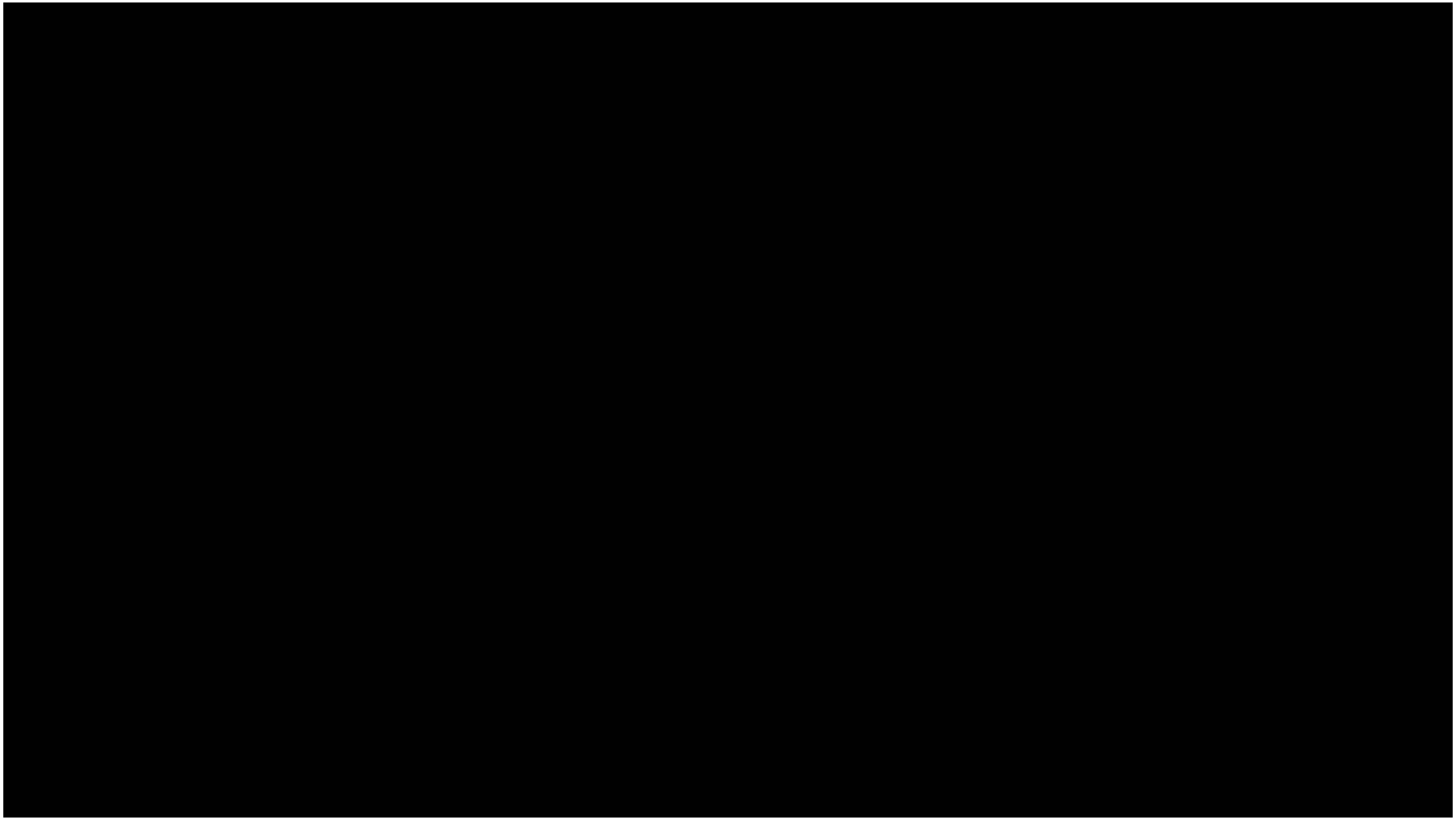
- **The AFM can operate in several modes, such as:**
  - **Contact mode**
    - the tip touches the specimen surface and senses inter-nuclear repulsive forces between the nuclei in the tip and nuclei in the sample (to avoid damage to the tip)
  - **Noncontact mode**
    - the probe is held just above the surface and the small electrostatic van der Waals attractive forces between atoms not in contact are measured
- **As with STM, a feedback circuit can be used to adjust the tip to maintain a constant force**
- **The tip motions can be recorded and converted into relief maps**
- **AFM produces 3D images.**



Nano-Lithography (Bottom-Up)

- These new investigation tools have the ability to – not just characterize– but actually move individual atoms and molecules
- A probe tip was used to deliver carbon monoxide molecules one at a time to an iron atom
- An interesting research is concerned with using an AFM tip to convey molecular ink to a substrate, enabling it to draw patterns with nanometric dimensions
- A key shortcoming of scanning probe procedure is the slow serial methods by which they operate, which limits their use mainly to laboratory applications





Random Questions

- Two Random students to ask each other a question

- Left column, seventh row, second one from the wall
- Right side, seventh row, first one from the aisle
- Punishment:

سبع سلاطين استسلطناهم من عند المستسلطانين
تقدر يا مسلطن يا مستسلطن تستسلطنلنا سبع سلاطين
زى ما استسلطناهم من عند المستسلطانيين

Green Electronics

Micro/Nano-fabrication (cont.)

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Spring 2020

Nanofabrication Techniques

- **1. E-beam (Electron beam)**
  - The e-beam technique uses an electron beam to expose an electron sensitive resist
  - The e-beam gun is part of a SEM
  - The resolution is about 10 nm
  - The beam control and pattern generation are achieved through a computer interface
  - E-beam lithography is serial, and hence, it has a low throughput

Nanofabrication Techniques

2. Scanned probe technique

- The scanning probe microscopy (SPM) systems are capable of controlling the movement of an atomically sharp tip in close proximity to - or in contact with - a surface with sub nanometer accuracy
- Piezoelectric positioners are used to achieve such accuracy
- High resolution images can be acquired by scanning the tip over a surface, while simultaneously monitoring the interaction of the tip with the surface
- In STM a bias voltage is applied to the sample and the tip is positioned close enough to the surface, so that a tunneling current develops through the gap

Nanofabrication Techniques

- **2. Scanned probe technique**
  - Because this current is extremely sensitive to the distance between the tip and the surface, scanning the tip in the X-Y plane-while recording the tunnel current-permits the mapping at the atomic scale
  - The amplified current signal is connected to the Z axis piezoelectric positioner through a feedback loop so that the current and therefore the distance are kept constant throughout the scanning
  - The surface topography is obtained by recording the vertical position of the tip

Nanofabrication Techniques

- **2. Scanned probe technique**
  - In AFM, the tip is attached to a flexible cantilever and brought in contact with the surface
  - The force between the tip and the surface is detected by sensing the cantilever deflection
  - A topographic image of the surface is obtained by plotting the deflection as a function of the XY position
  - In a more common mode of operation a feedback loop is used to maintain a constant deflection, while the topographic information is obtained from the cantilever vertical displacement

Nanofabrication Techniques

2. Scanned probe technique

- Electrons emitted from a biased SPM tip can be used to expose an organic resist, the same way e-beam lithography does
- The exposure is done by moving the SPM tip over the surface, while applying a bias voltage high enough to produce an emission of electrons from the tip (a few tens of volts)
- In **dip pen nanolithography (DPN),** the tip of an AFM operated in air is inked with a chemical of interest and brought in contact with a surface

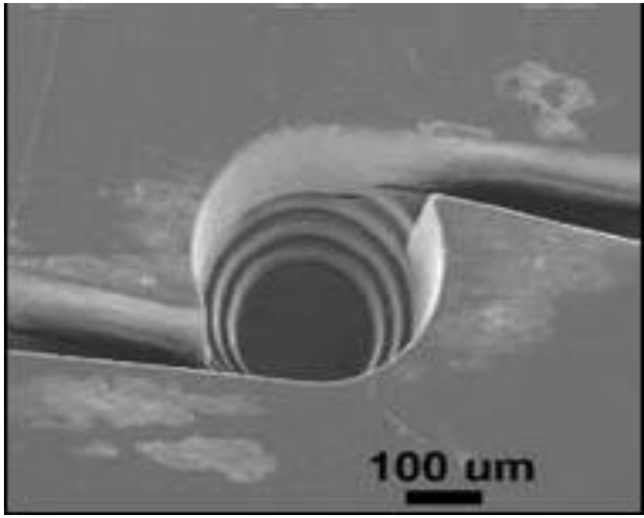
Nanofabrication Techniques

- **2. Scanned probe technique**
  - The ink molecules flow from the tip onto the surface as with a fountain pen
  - The water meniscus (curvature) that naturally forms between the tip and the surface enables the diffusion and transport of the molecules
  - Inking can be done by dipping the tip in a solution containing a small concentration of the molecules followed by a drying step

Nanofabrication Techniques

3. Laser Machining

- Focused high power laser pulses can ablate material (explosively remove it as fine particles and vapor) from a substrate
- Incorporating such a laser in a computer-numerical-controlled system enables precision laser machining
- Metals, ceramics, silicon, and plastics can be laser machined
- Holes as small as tens of microns in diameter, with aspect ratios greater than 10:1, can be produced
- Laser machining is most often a serial process, but with mask-projection techniques, it becomes a parallel process



Random Questions

- Two Random students to ask each other a question

- Left side, first row, second one from the wall

- Right side, second row, first one from the wall

- Punishment:

Provide an entertaining game to the class

Nanofabrication Techniques

4. LIGA

- German abbreviation and stands for Lithographie, Galvanoformung and Abformung (lithography, electrodeposition and molding)
- The LIGA Fabrication process provides the possibility to produce micromechanical structures with very high aspect ratios compared to other microelectromechanical technologies (up to 300:1)
- The height of the manufactured pieces can be 100 microns to a couple of millimeters

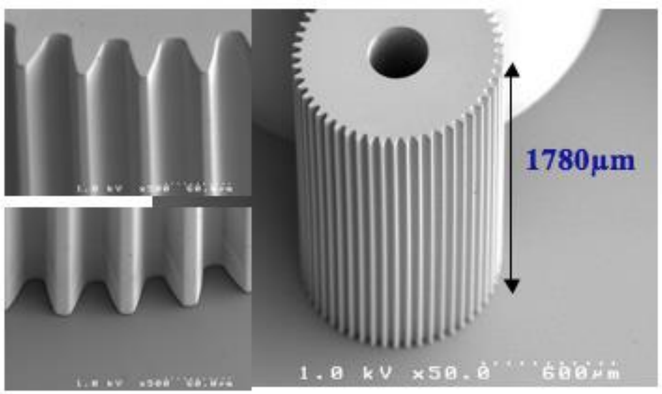
Nanofabrication Techniques

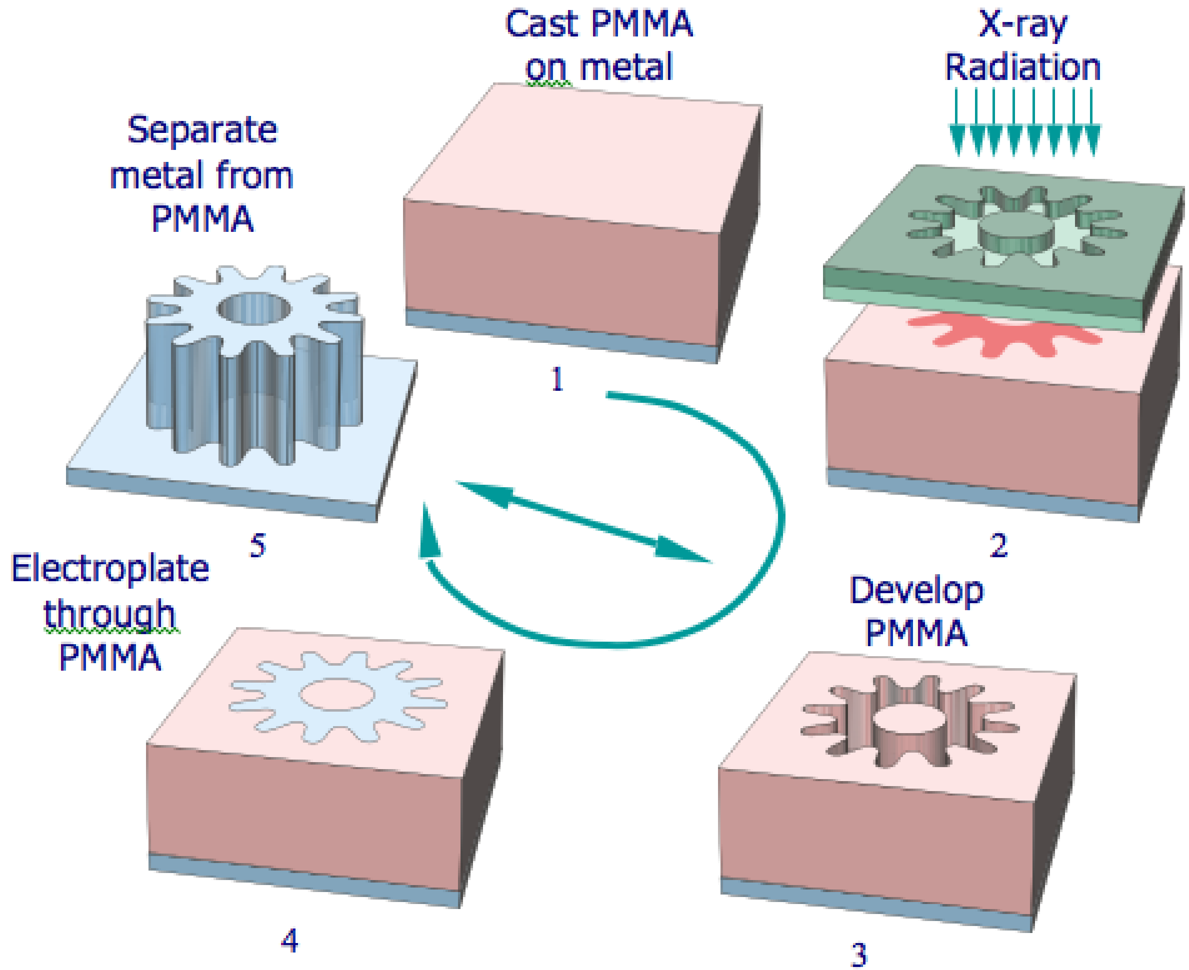
LIGA

- The principle of the LIGA process consists of depositing a relatively thick layer of a polymer sensitive to X-rays on top of a conductive substrate or one covered with a conductive seed layer
  - multiple coats of photoresist during spinning the substrate wafer for thicknesses of up to a few hundred microns
  - plates of PMMA (poly-methyl-meth-acrylate), a thicker polymer layers (millimeters) used as a photoresist
- After exposure through an appropriate X-ray-mask, a developer removes either the exposed (positive photoresist) or the unexposed (negative) areas of polymer
- Metal layers are grown by electroplating in the spaces now free from cover
- Having removed the unwanted areas of the polymer, the resulting metallic structure can be used

Nanofabrication Techniques

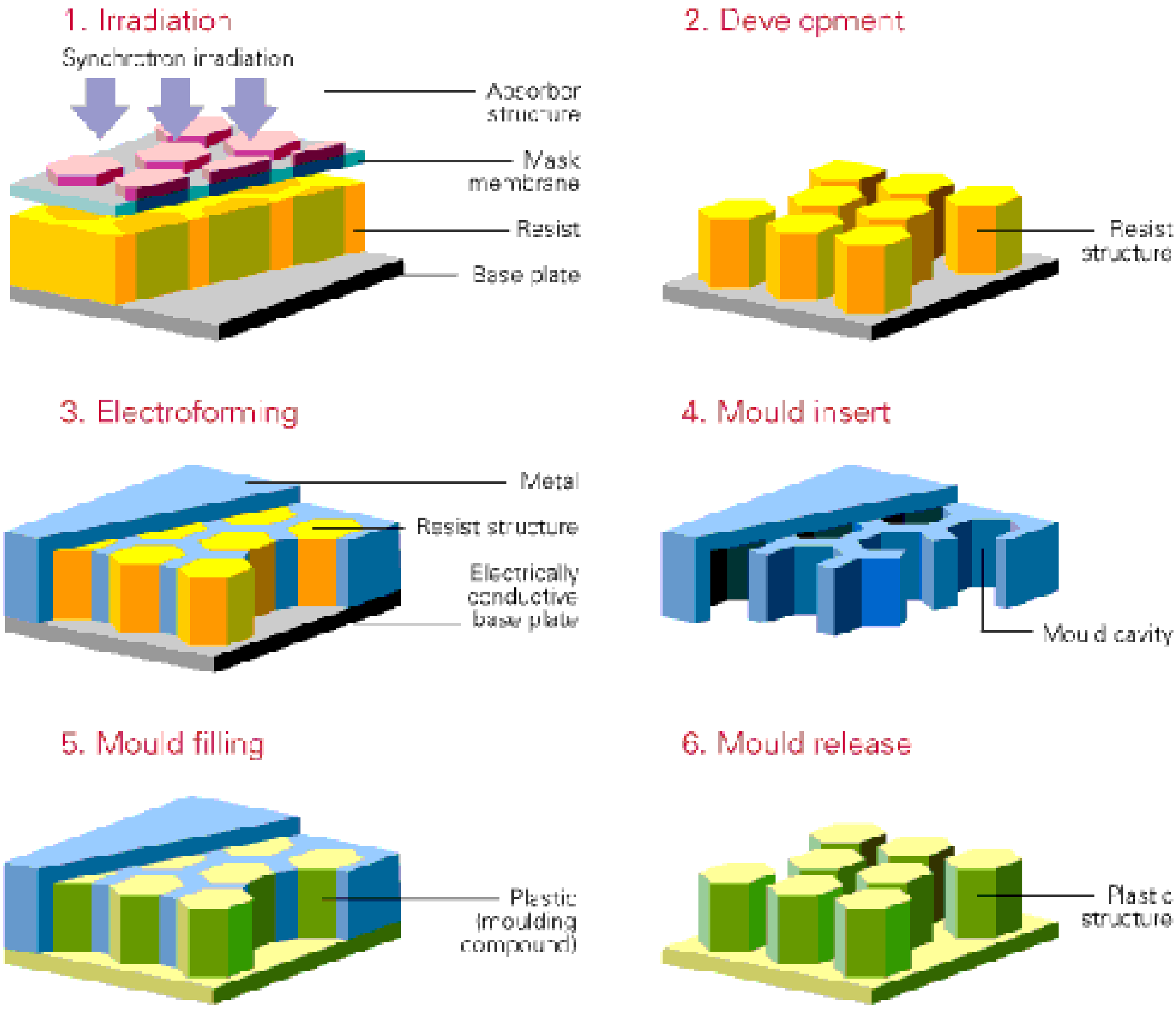
- LIGA





Nanofabrication Techniques

- LIGA
  - The process may be stopped at this point with a metal microstructure suitable for some purposes such as gears
  - Alternatively, the metal can be used as a mold for plastic parts (the "A" in LIGA)

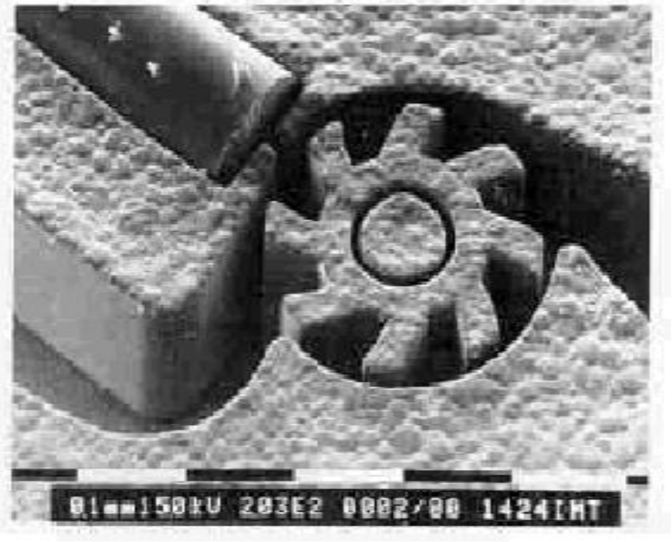


Nanofabrication Techniques

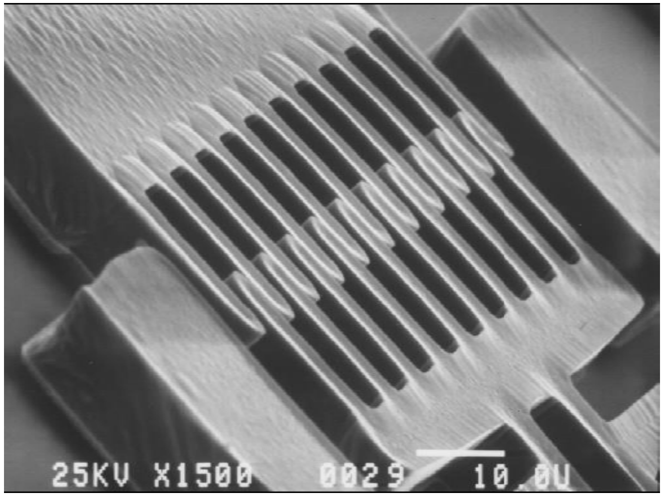
- **LIGA**
  - **Advantages:**
    - high aspect ratios
    - very sharp vertical sidewalls as well as the possibility to produce three-dimensional structures
  - **Disadvantages:**
    - the need of high-energy X-rays
    - the expensive X-ray masks needed for exposure make the cost for the process high
  - Mold formation using optical lithography is often called "poor man's LIGA" due to the small aspect ratios
  - Companies providing the necessary tools for LIGA to multiple users can reduce the production cost

Advanced Process Tools

- **LIGA examples (Metals)**
  - **Microfluidic device**



  - **Micromechanical actuator (capacitive comb drive)**



Random Questions

- Two Random students to ask each other a question

- Middle side, second last row, second one from the wall

- Middle side, third row, first one from the wall

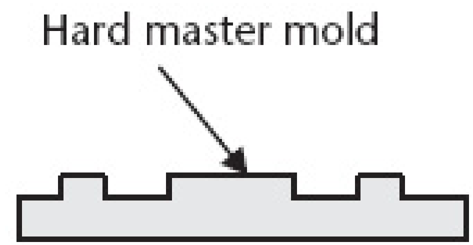
- Punishment:

Provide an entertaining game to the class

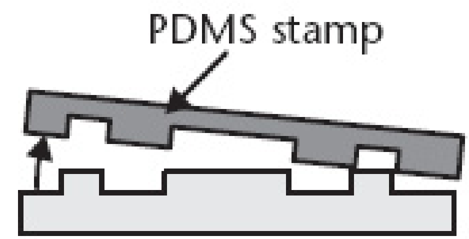
Nanofabrication Techniques

5. Micro-contact Printing/Soft Lithography

- Production of the original, hard, 3D master pattern



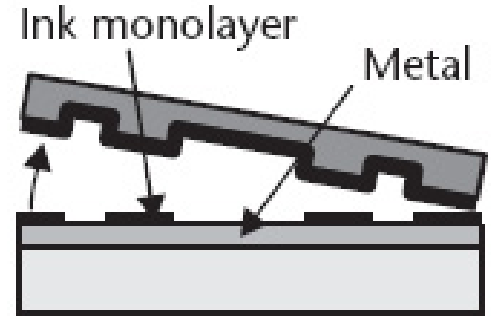
- A mold of an elastomer, usually poly-di-methyl-siloxane (PDMS), is made against the master, then peeled off to create a stamp



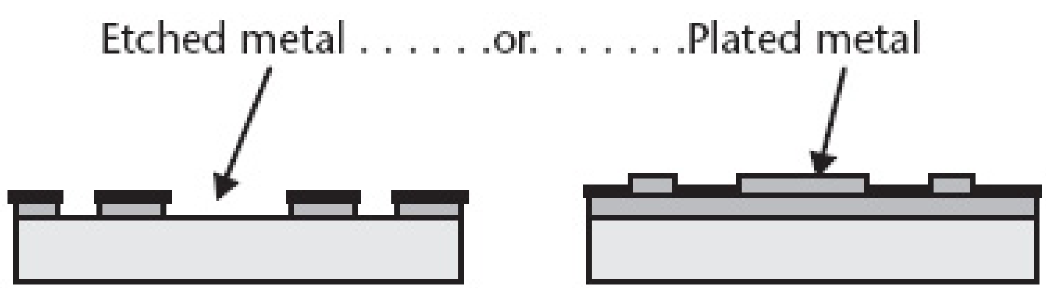
- An “ink,” is poured onto the PDMS stamp and dried

Nanofabrication Techniques

- **5. Micro-contact Printing/Soft Lithography**



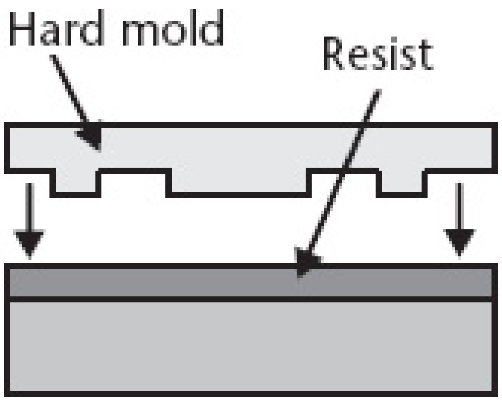
  - The inked stamp is then held against a substrate coated with gold, silver, or copper, then removed
  - The coating is used as an etch mask for the metal
  - The metal can then be used as an etch mask for the underlying substrate, such as silicon
  - Alternatively, selective plating of the metal can be carried out



Nanofabrication Techniques

6. Nano-imprint Lithography

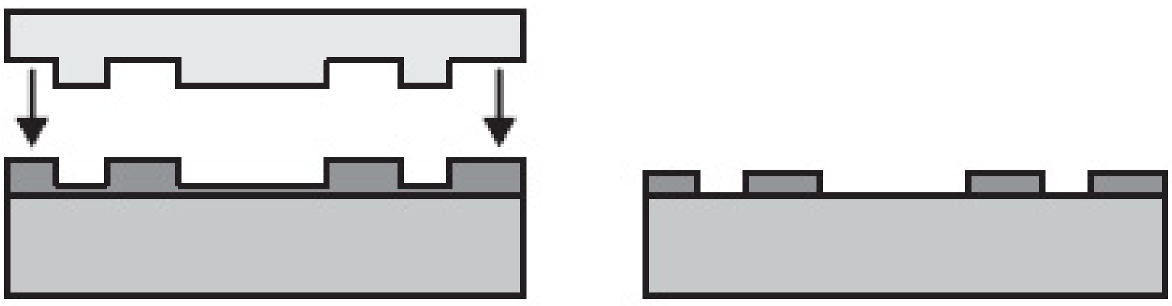
- Starts with a mold of etched silicon, silicon dioxide, or other hard material created using optical or electron-beam lithography
- The substrate is coated with a 50nm to 250nm resist layer, which does not need to be photosensitive
- The resist is heated so that it flows easily under pressure



Nanofabrication Techniques

6. Nano-imprint Lithography

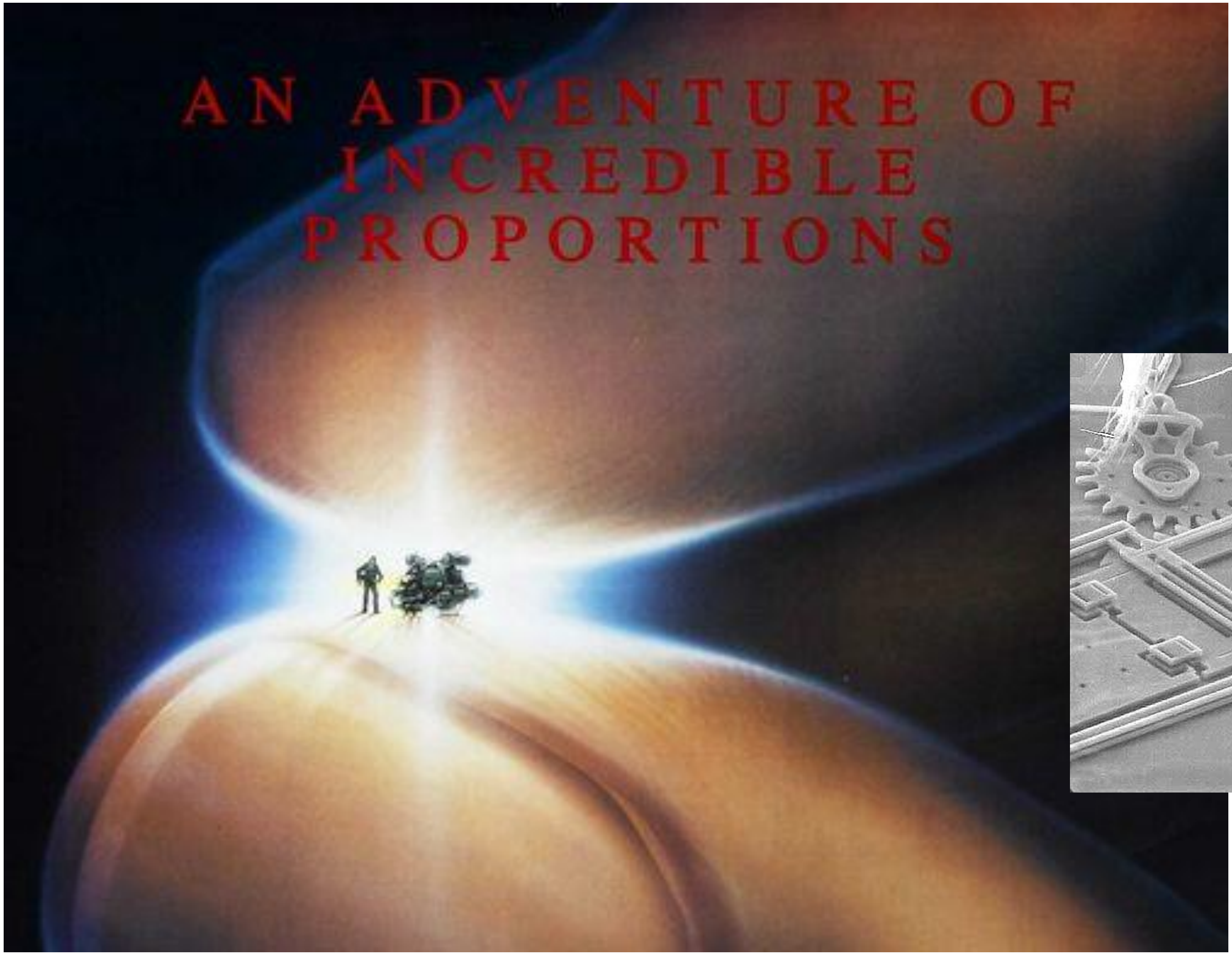
- The mold is then pressed into the resist
- The mold is removed, leaving an unintentional residue of resist
- This residue is stripped using vertical etching

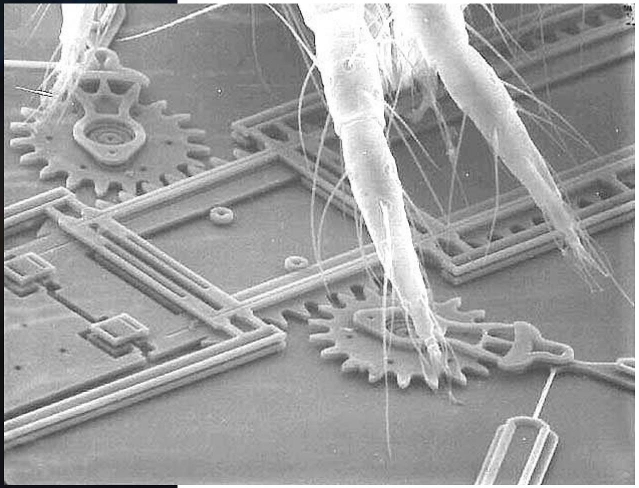


- Features **25nm** wide with smooth sidewalls have been demonstrated

MEMS/NEMS

Really small devices

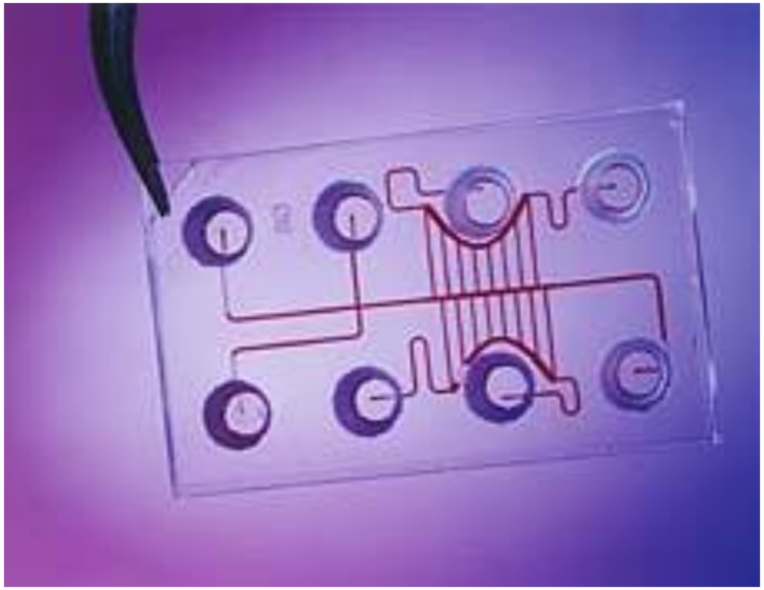


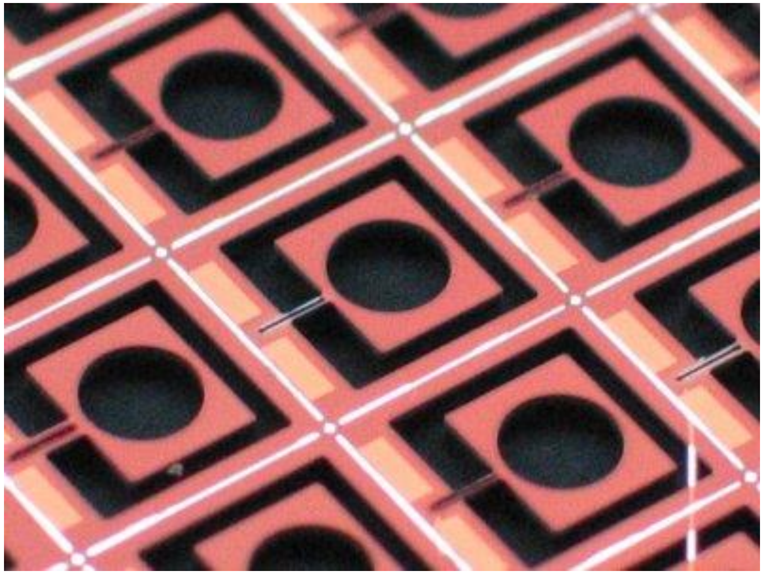


What are MEMS/NEMS?

- MEMS/NEMS = Micro/Nano-Electro-Mechanical Systems
  - Tiny machines (micro and nano scale)
  - Not just micro/nano-fabrication
  - Enabling technology to augment as they are fabricated for a specific application (non-standardization)
  - Miniaturization for performance enhancement

Examples

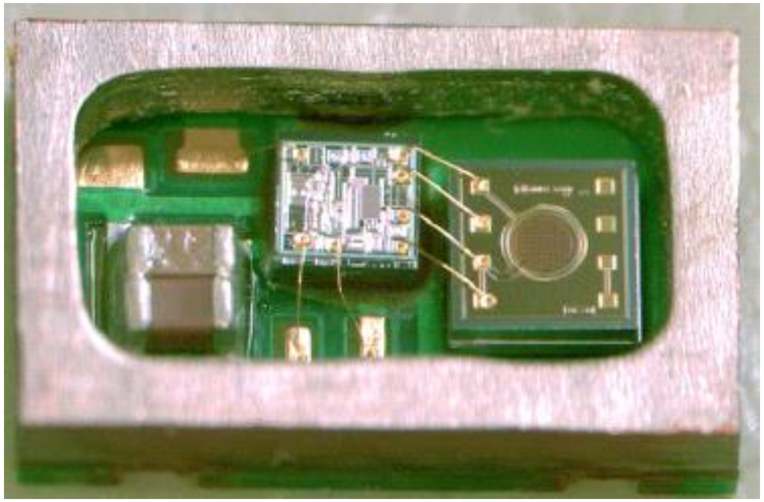




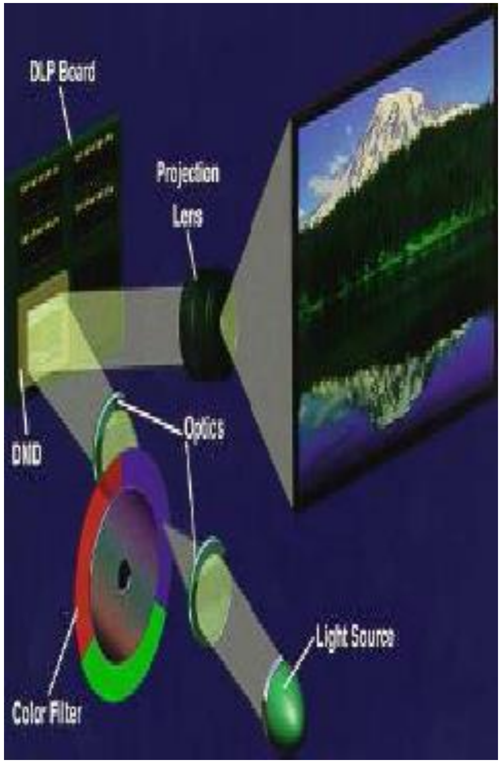
Lab-chips from Agilent

Energy harvester from Perpetuum

Examples



Microphone from Knowles

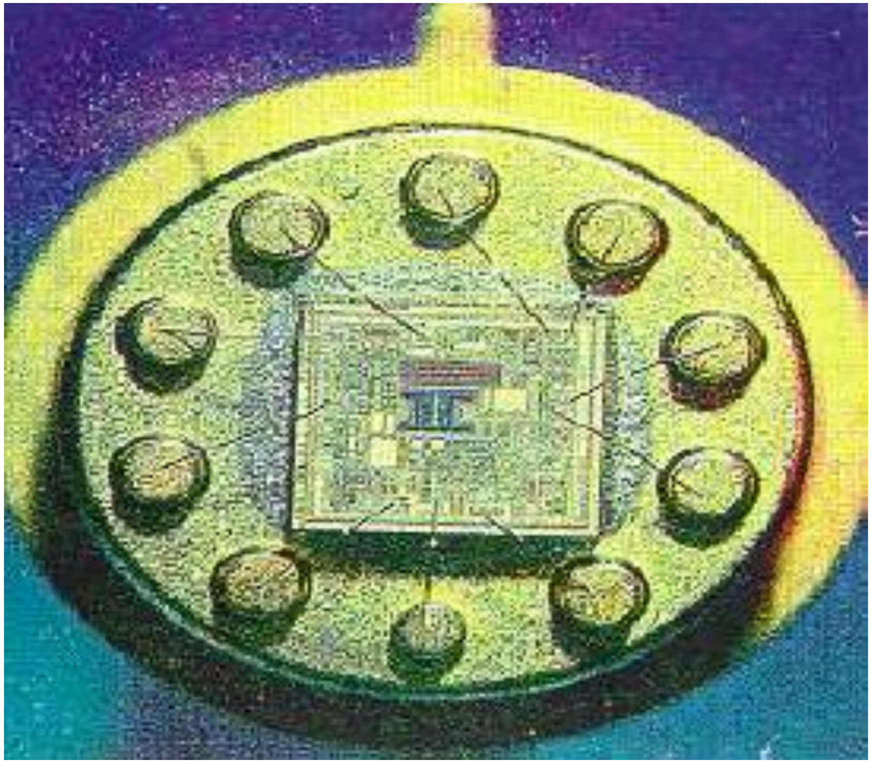


Digital Micro-mirrors Device (DMD) from TI

Examples

Inkjet Nozzle from

HP



Accelerometer from
Analog Devices

Examples

Spectrometer from Si-Ware

MEMS Advantages

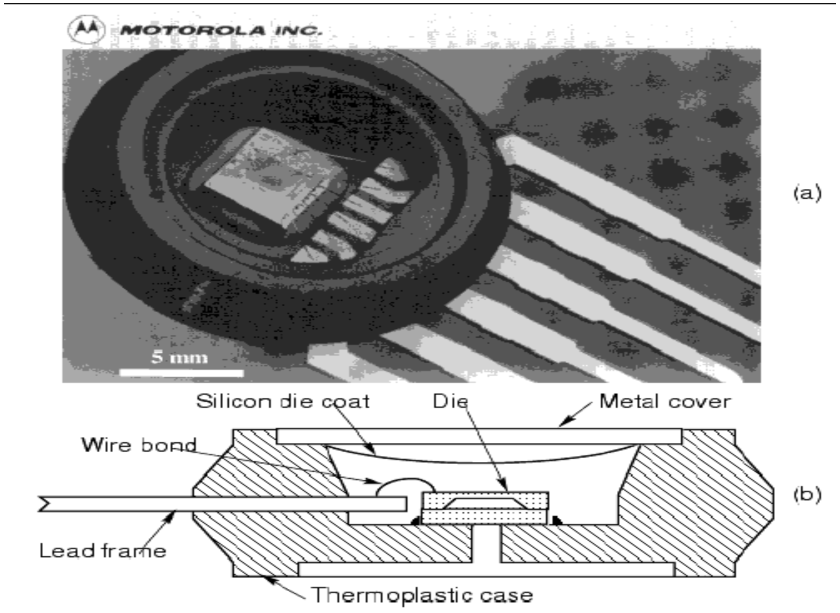
- MEMS devices integrate multiple functions like sensing, decision making and control functions on a single chip
- High Sensitivity
- Portability
- Low power consumption
- Easy to maintain and replace

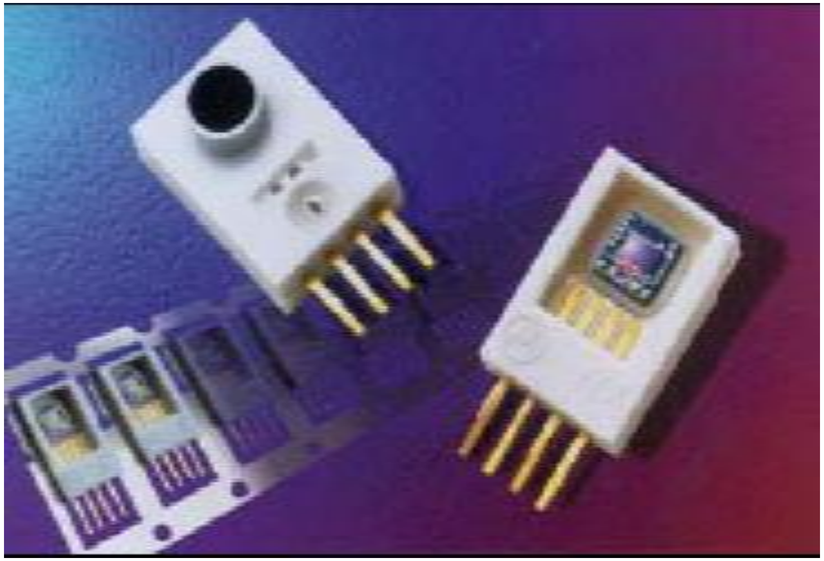
Micro/Nano Fabrication

- No such thing as "Shrinking machines"
- Must learn how to build them small

MEMS Packaging

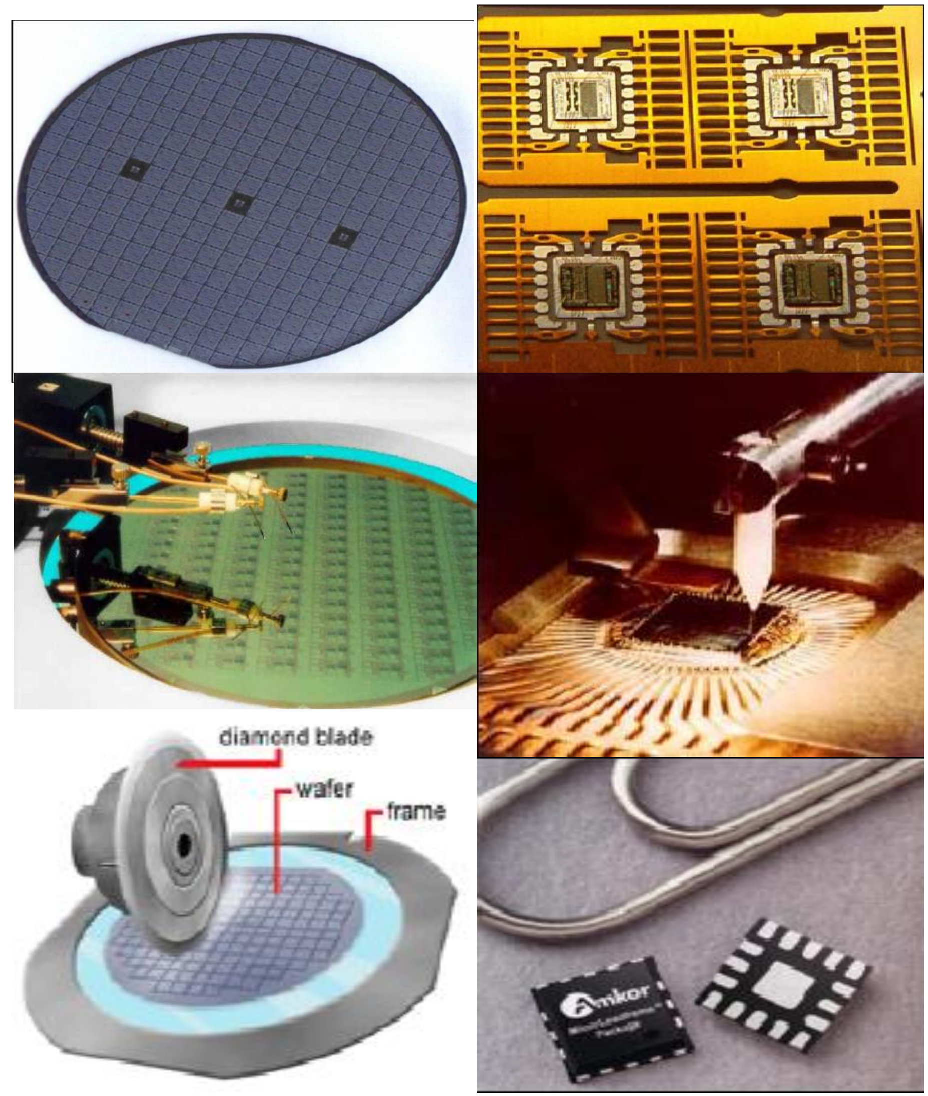
- Micro device is not useful until it is placed in a "package" that allows it to interface with the real world
- MEMS packaging is extremely difficult and expensive. 80% of cost of MEMS is in package.





MEMS Packaging

- **CMOS packaging includes:**
  - **Silicon wafer with dies**
  - **Wafer level probe test**
  - **Dicing**
  - **Die attach to lead frame**
  - **Wire bonding**
  - **Final packaged chip**



MEMS Packaging

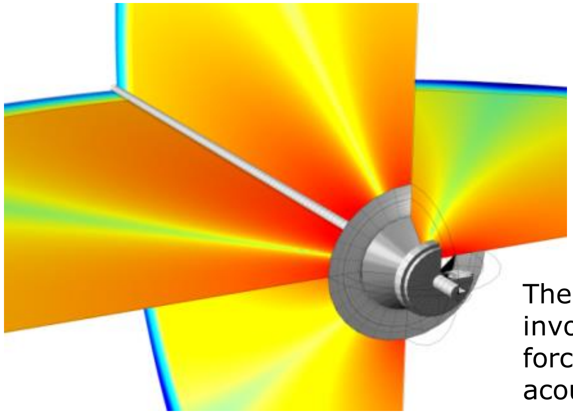
- **Problems:**

  - MEMS device cannot be tested at the wafer level. It must be released in order to test**!**
  - MEMS part must be handled in clean room environment
  - MEMS part typically tested after dicing, cleaning, release, and packaging—after much cost has already been incurred
  - MEMS part often requires vacuum sealing

Multi-Physics Device Simulator

COMSOL Multiphysics

- Multiphysics is the combination of several physics phenomena when describing a process
- In modeling and simulations, these descriptions are based on the laws of physics
- There is one precise way to present the laws of physics, and that is by means of differential equations*

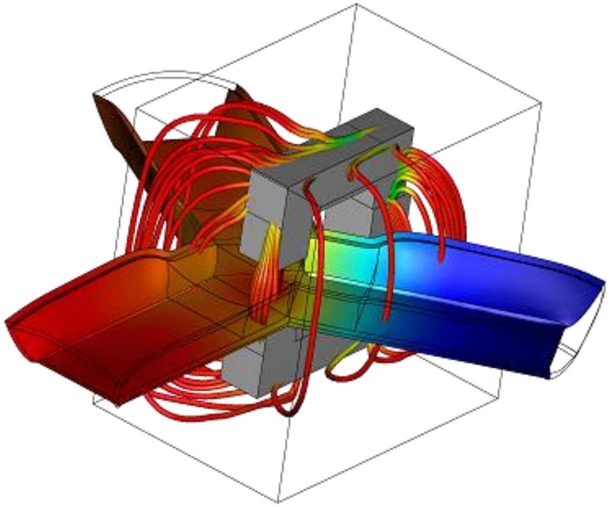


The description of a loudspeaker involves electromagnetic fields and forces, structural analysis, and acoustic pressure fields in the one model.

* Feynman "Famous Lectures"

COMSOL's Methodology for Modeling Multiphysics Phenomena

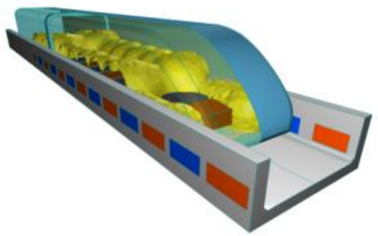
- Development goals:
  - To create a software where scientists and engineers can formulate any system of partial differential equations (PDEs) based on the laws of physics
  - To formulate user interfaces, based on the above methods, for the most common areas in applied physics and engineering



Microwave-thermal-structural multiphysics couplings in a waveguide circulator

COMSOL's Methodology for Modeling Multiphysics Phenomena

- Equation-based modeling
  - The modeling interface is based on an equation interpreter that formulates a finite element discretization, "on the fly", for the **fully coupled** system
- Predefined modeling interfaces for different fields of applied physics, including multiphysics couplings
  - Due to the underlying technology, properties, sources, sinks, and boundary conditions can be functions of the modeled variables and their partial derivatives
  - The full equations are also available in the user interface for further manipulation



Electromagnetic fields and forces coupled to Newton's law to compute the acceleration of a Maglev train

Green Electronics

Course Project

Dr. Hassan Mostafa

د/ حسن مصطفى

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Cairo University

Spring 2020

Course Project (20 marks)

- Part1: **Department Knowledge Impact (15 marks)**
  - In this project, it is required to find and implement simple and technology-based ideas to use our department knowledge to be <u>help charity organizations. The implemented idea should carry the **group names** and be considered as a stamp for the students on their department/society/life.</u>
- Constraints
  - **Students group of 5-10 students**
  - The group should do all the logistics/approvals/paper work required to ensure the applicability of the idea.
  - The group deliver a maximum of 5 minutes video showing their project idea, impact, innovation, marketing, real implementation, names, and benefits to the department/society. All the project members should **show up** in the video.
  - It is acceptable that more than one group build a larger project with detailed explanation of each group role. **This must be approved from the course instructor by email**

Course Project (20 marks)

- Deadlines:
  - **April 8, 2020 (12 noon)**
    - Each group should submit ONE **hard copy** page with the following:
      - Group names
      - Charity agency/idea/impact summary
  - **May 30, 2020 (12 noon)**
    - Each group should submit their video with the implemented project. **Exceptions might be applied, if justified.**
- Project grading scheme:
  - 25% Presentation skills in the video
  - 25% Society impact and idea sustainability
  - 50% Idea practical implementation
- Late delivery:
  - **Penalty is -10% mark per day**
  - **No video means ZERO marks out of 15.**

Course Project (20 marks)

- Part2: **COMSOL Simulations (5 marks)**
  - In this project, it is required to design a MEMS device of the course MEMS devices using COMSOL software and calculate all the related figures of merit.
- Constraints
  - **Individual project**
  - Deadline: **May 30, 2020 (12 noon)**
  - **Penalty is -10% mark per day**
  - **Random students will be asked to present their project and asked about the steps. No answer means zero grade.**
  - **Delivery: Each student should submit a hardcopy report of her/his design (maximum 5 pages excluding the cover page).**

Green Electronics

Lecture 5-7
MEMS/NEMS Applications

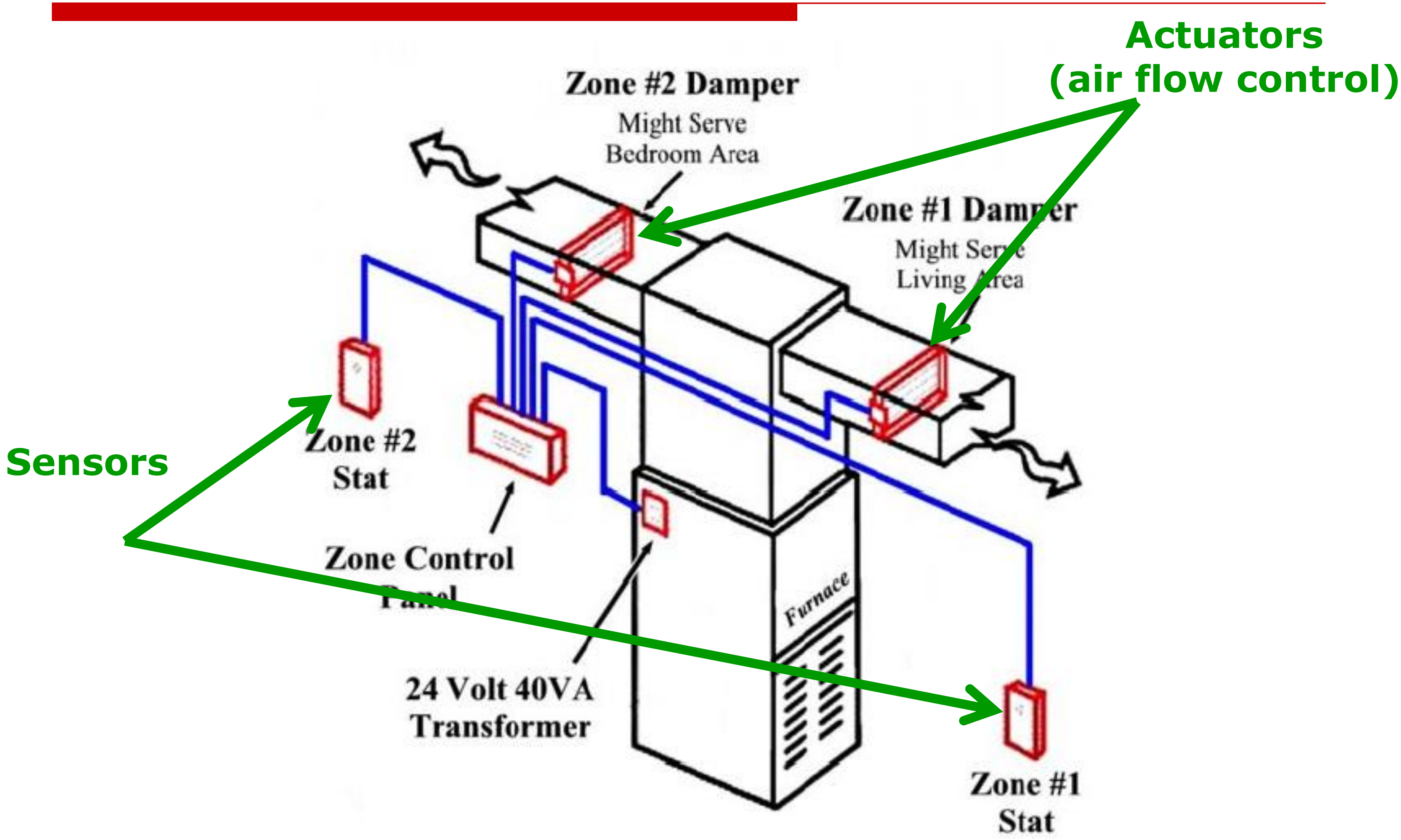
Dr. Hassan Mostafa
hmostafa@uwaterloo.ca
Cairo University

Spring 2020

Sensors and Actuators

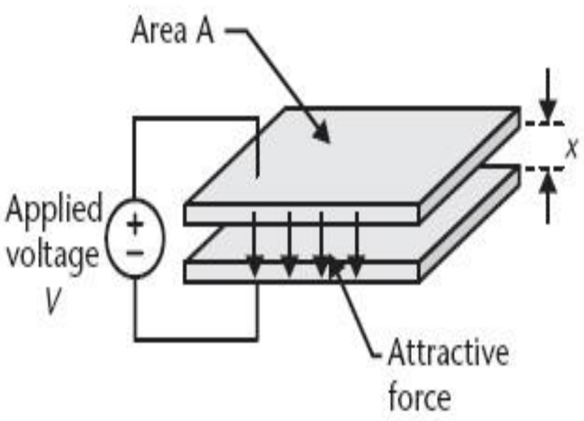
- **Sensor**
  - A device that converts an environmental condition into an electrical signal
- Actuator
  - A device that converts a control signal (usually electrical) into mechanical action (motion)
- Basic components of a control system
  - Sensor
  - Actuator
  - Power supply
  - Controller

Home heating example



Actuation methods

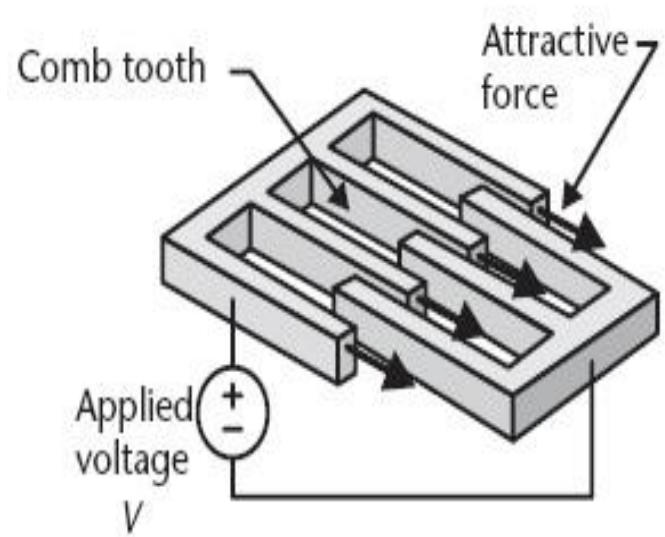
- **Electrostatic actuation**
  - It relies on the attractive force between two conductive plates
  - An applied voltage results in an attractive electrostatic force between the two plates
  - If *C is the capacitance between two* parallel plates, *x is the spacing between them, and V is an* externally applied voltage, the electrostatic force is then ($0.5 * C * V^2$)/x



Actuation methods

Electrostatic actuation

- Electrostatic comb actuators are a variant that includes two comb sets of inter-digitated “teeth” that are offset relative to each other
- An applied voltage brings the two combs together such that the teeth become alternating
- Designers have favored comb actuators over parallel-plate actuators because they allow a larger displacement (tens of micrometers are feasible)



Actuation methods

- **Piezoelectric Actuation**
  - **Piezoelectricity** is the ability of some crystals to create mechanical stress, or motion by expanding or contracting in response to an applied voltage
  - Piezoelectric actuation can provide significantly large forces, especially if thick piezoelectric films are used

Actuation methods

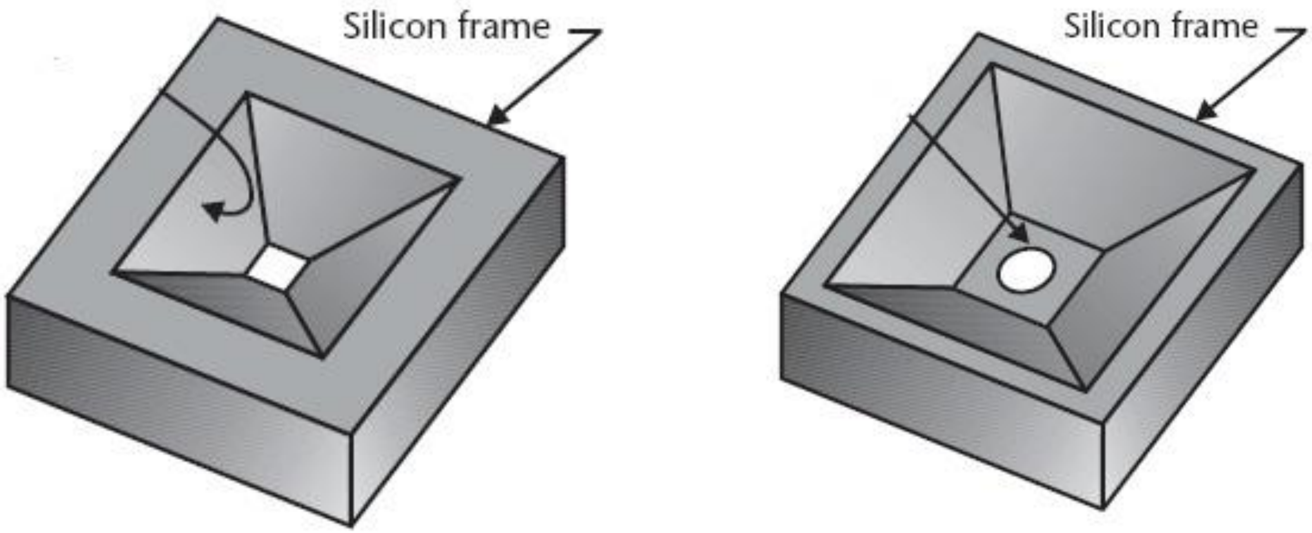
- **Thermal Actuation**
  - It consumes more power than electrostatic or piezoelectric actuation
  - **Two layers approach**
    - The difference in the thermal expansion coefficients between two joined layers of dissimilar materials cause bending with temperature
    - One layer expands more than the other as temperature increases
    - This results in stresses at the interface and consequently bending of the stack
    - The amount of bending depends on the difference in coefficients of thermal expansion and absolute temperature

Actuation methods

- **Magnetic Actuation**
  - Electrical current in a conductive element that is located within a magnetic field gives rise to an electromagnetic force (called the Lorentz force) in a direction perpendicular to the current and magnetic field
  - This force is proportional to the current, magnetic flux density, and length of the element

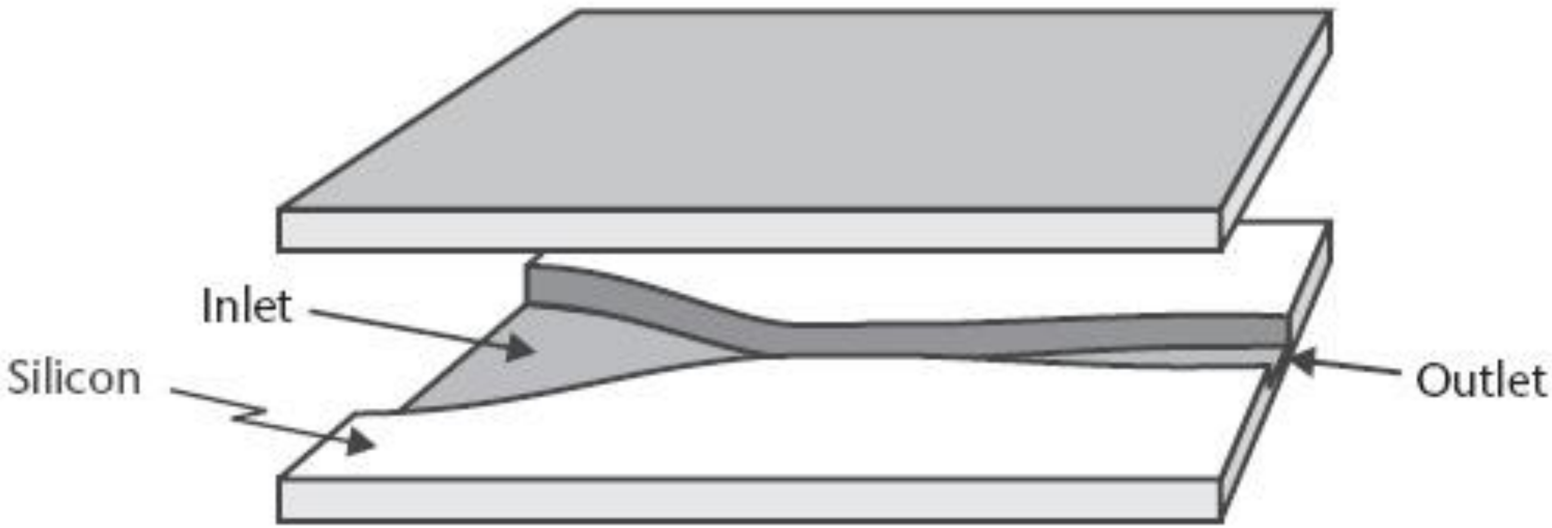
Passive Micro-machined Mechanical Structures

- **Fluid Nozzles**
  - Nozzles are among the simplest microstructures to fabricate using etching of silicon, electroforming, or laser drilling of a metal sheet
  - Forming nozzles of circular or arbitrary shape in silicon involves additional fabrication steps



Passive Micro-machined Mechanical Structures

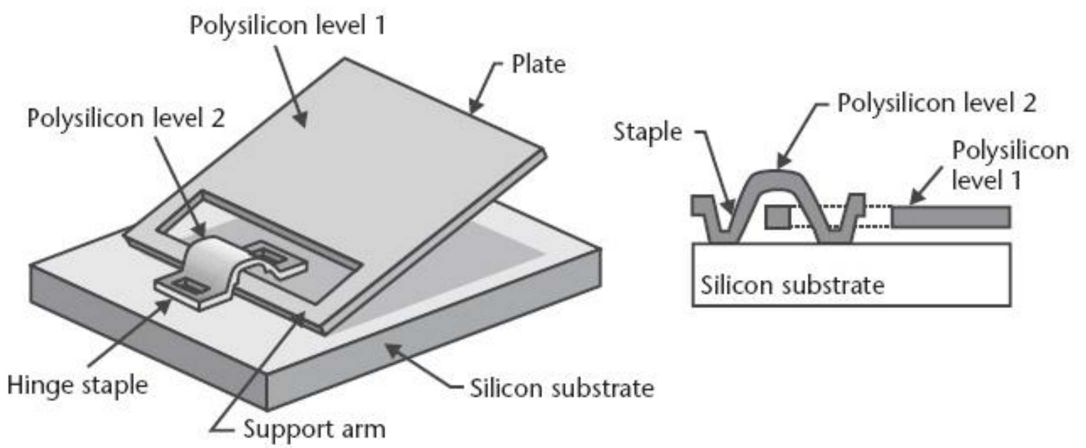
- **Fluid Nozzles**
  - Nozzles types:
    - *Top shooters: they are* oriented perpendicular to the surface of the wafer as *in the inkjet field*
    - *Side shooters: they are oriented parallel* to the wafer surface as in the fluid flow field



Passive Micro-machined Mechanical Structures

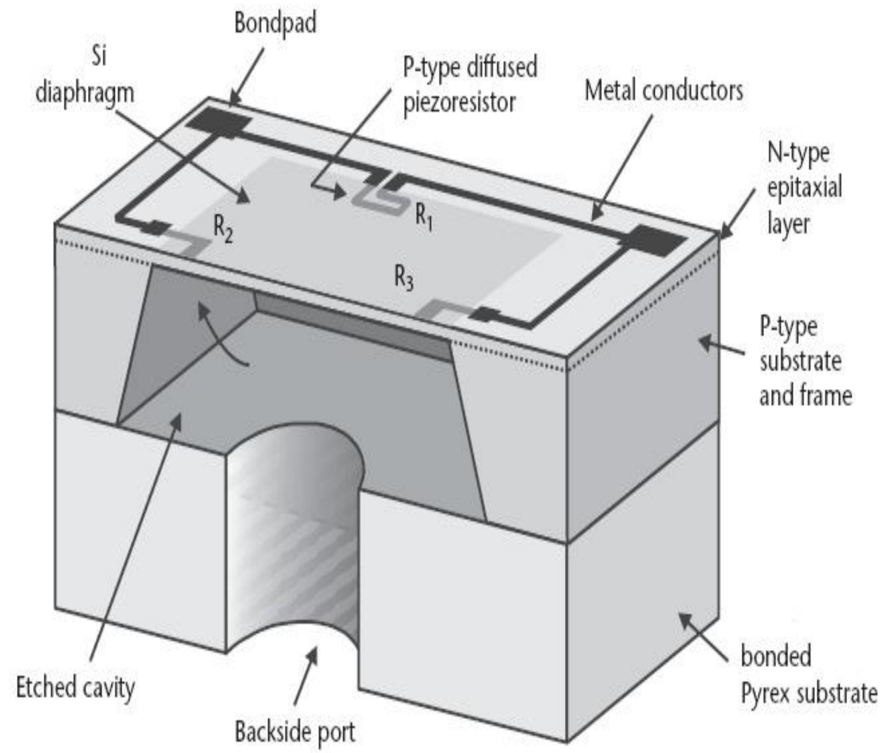
Hinge Mechanisms

- At the microscopic scale, hinges extend the utility of the 2D surface micromachining technology into the 3D
- The hinge structure is simple, consisting of a plate and a support arm made of a first polysilicon layer
- A staple made of a second polysilicon layer captures the plate support arm
- The staple is anchored directly to the substrate
- The fabrication utilizes the polysilicon surface micro-machining process



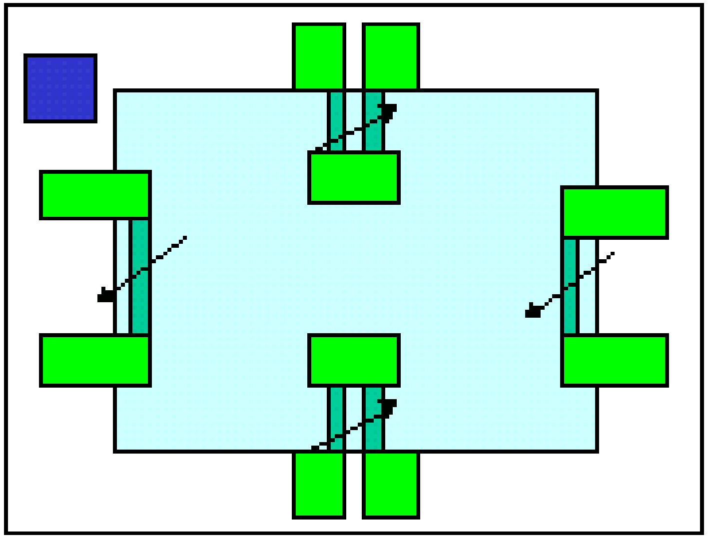
Sensors and Analysis Systems

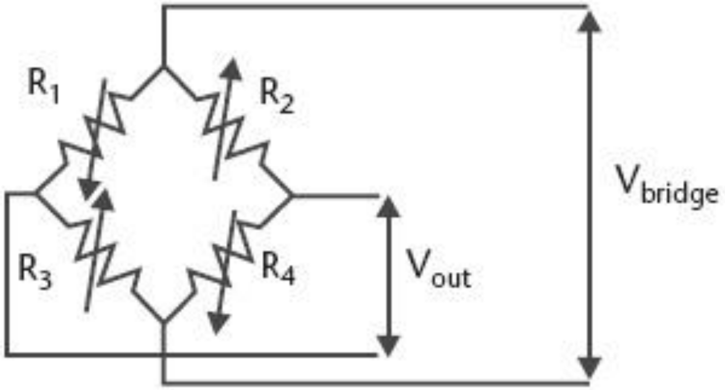
- **Pressure Sensor:**
  - The vast majority use piezoresistive sense elements to detect stress in a thin silicon diaphragm in response to a pressure load
  - The basic structure of a piezoresistive pressure sensor consists of four sense elements in a Wheatstone bridge configuration that measure stress within a thin silicon membrane



Pressure Sensor:

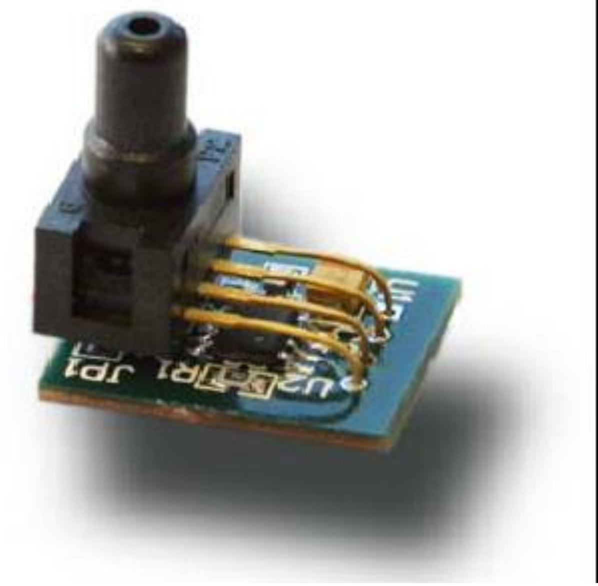
- The stress is a direct consequence of the membrane deflecting in response to an applied differential pressure across the front and back sides of the sensor
- The membrane deflection is typically less than one micrometer
- Four diffused *p-type* piezoresistors at the points of highest stress, which occur at the center edges of the membrane
- The four resistors should be identical under zero applied pressure





Sensors and Analysis Systems

- **Pressure Sensor:**
  - **Sensitivity:**
    - The ratio between the normalized output voltage (measured bridge voltage in mV divided by the bridge supply voltage in V) and the applied pressure in Pa
    - Units: (mV/V)/Pa
    - Desired to be as maximum as possible
  - **Zero offset**
    - Offset voltage measured under zero applied pressure
    - This occurs due to mismatch in resistors or temperature variations
    - Desired to be Zero



Random Questions

- Two Random students to ask each other a question

- Left side, fourth row, third one from the wall

- Right side, second row, first one from the aisle

- Punishment:

Say ABC backwards from Z to A

Accelerometers

- A sensor that detects change in velocity
- Most common application for MEMS accelerometers
  - Air bag deployment.

Accelerometers

- Accelerometers widely used for monitoring vibrations in industrial machinery

- Automotive applications: Brake sensor and bounce sensor

Accelerometers

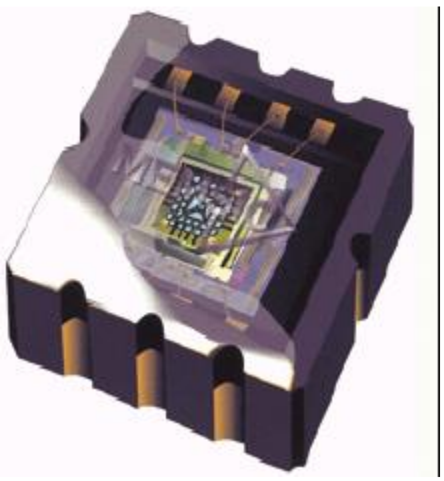
- The first demonstration of a micromachined accelerometer took place in 1979 at Stanford University
- **Basic structure**
  - Inertial mass suspended from a spring
  - They differ in the sensing of the relative position of the inertial mass as it displaces under the effect of an externally applied acceleration
  - Sensing methods such as capacitive or piezoelectric
- **Specifications**
  - Full-scale range (in G) <G=9.81 m/sec^2>
  - Sensitivity (in V/G)
  - Resolution (in G)
  - Bandwidth (in Hz) <acceleration reading times/sec>
  - Cross-axis sensitivity
  - Immunity to shock

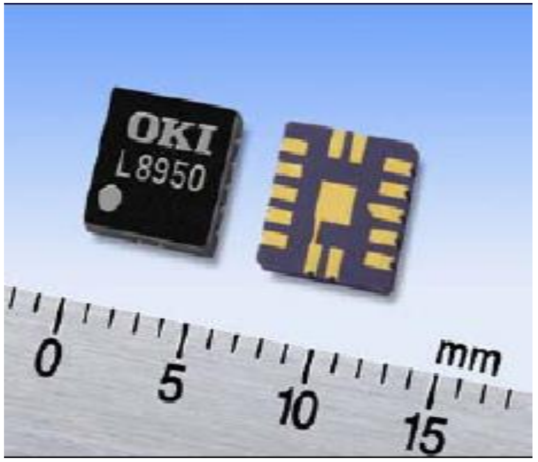
Accelerometers

- Accelerometers for airbag crash sensing are rated for a full range of ±50G and a bandwidth of about 1.0 kHz
- Accelerometers for engine vibration have a range of ±1G, but must resolve small accelerations (<100 μG) over a large bandwidth (>10 kHz)
- Accelerometers for pacemakers
  - Incorporate multi-axis accelerometers to monitor the level of human activity, and correspondingly adjust the stimulation frequency
    - Full scale range of ±2G and a bandwidth of less than 50 Hz, but they require extremely low power consumption for battery longevity
- Accelerometers for military applications can exceed a rating of ±1,000G

Accelerometers

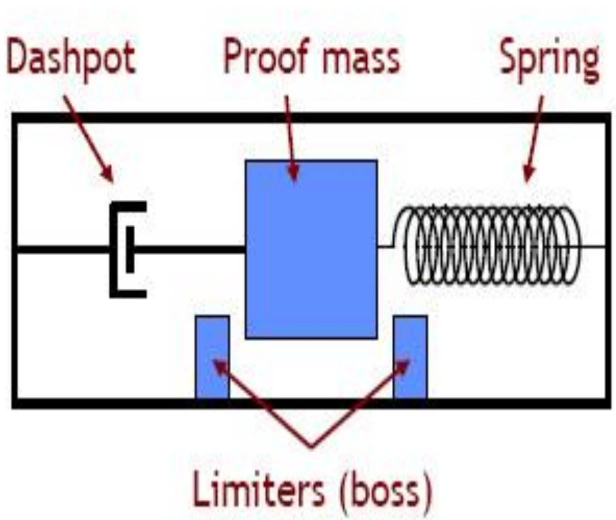
- Cross-axis sensitivity is the immunity of the sensor to accelerations along directions perpendicular to the main sensing axis
- Shock immunity is an important specification for the protection of the devices during handling or operation
  - The test is performed by dropping the device from a height of one meter over concrete
  - The shock impact can easily reach a dynamic peak of 10,000G



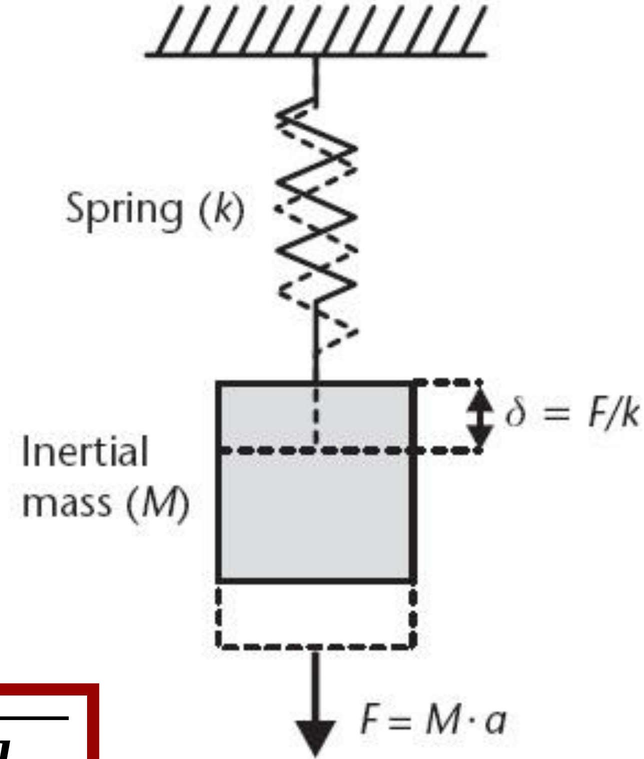


Accelerometers

- Basic structure



Movement of proof mass is proportional to acceleration.



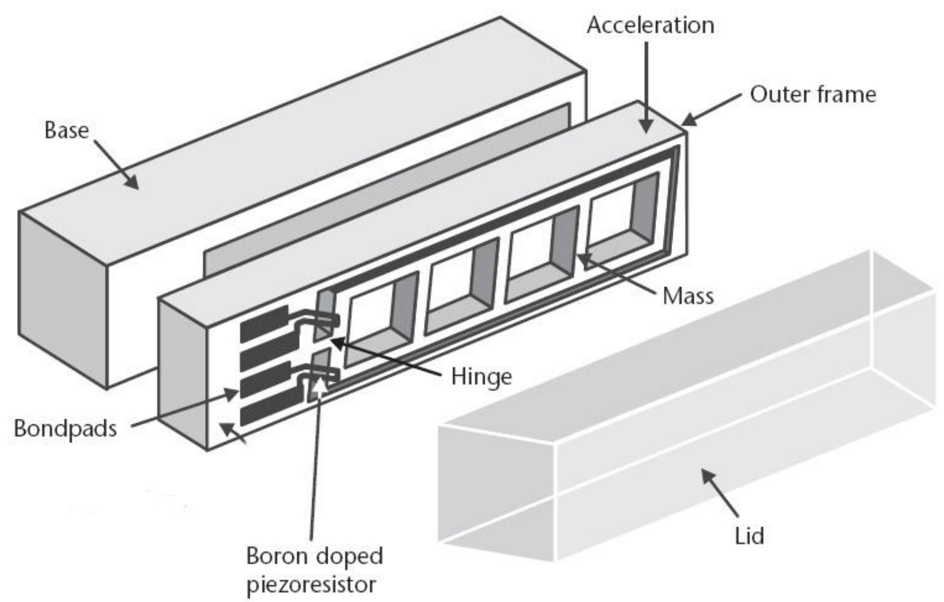
$$f_{resonance} = \frac{1}{2\pi}\sqrt{\frac{k}{M}}$$

Accelerometers

- Types for study
  - Piezoresistive Bulk Micromachined Accelerometer
  - Capacitive Bulk Micromachined Accelerometer
  - Capacitive Surface Micromachined Accelerometer

Piezoresistive Bulk Micromachined Accelerometer

- It consists of three substrates:
  - a lower base
  - a middle core containing a hinge-like spring, the inertial mass, and the sense elements
  - a top protective lid



Piezoresistive Bulk Micromachined Accelerometer

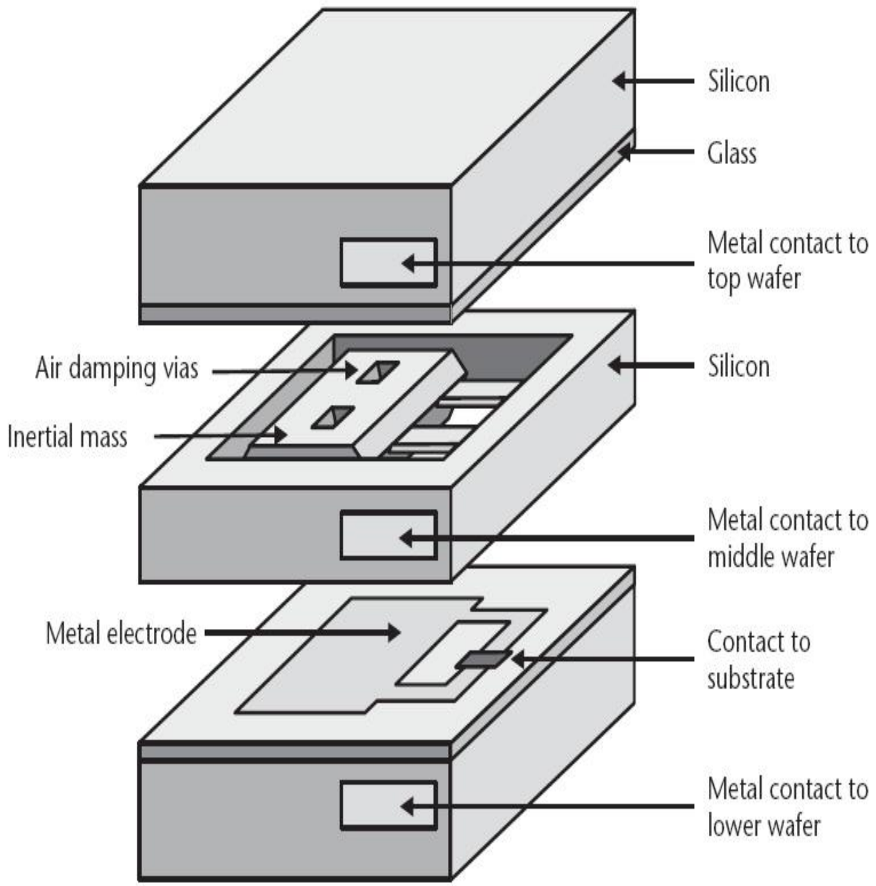
- The inertial mass sits inside a frame suspended by the spring
- Two thin piezoresistive elements in a Wheatstone bridge configuration span the narrow 3.5-μm gap between the outer frame of the middle core and the inertial mass
- The piezoresistors are only 0.6 μm-thick and 4.2 μm-long and are very sensitive to displacements of the inertial mass
- The output in response to an acceleration equal to 1G in magnitude is 25mV for a Wheatstone bridge excitation of 10V
- The thick and narrow hinge structure allows displacement within the plane of the device, but it is very stiff in directions normal to the wafer, resulting in high immunity to off-axis accelerations

Piezoresistive Bulk Micromachined Accelerometer

- The outer frame acts as a stop mechanism that protects the device in the event of excessive acceleration shocks
- It takes 6,000G for the inertial mass to touch the frame
- The device can survive shocks in excess of 10,000G
- Open apertures reduce the weight of the inertial mass and combine with the stiff hinge to provide a rather high resonant frequency of 28 kHz

Capacitive Bulk Micromachined Accelerometer

- It consists of a stack of three bonded silicon wafers, with the hinge spring and inertial mass incorporated in the middle wafer
- The inertial mass forms a moveable inner electrode of a variable differential capacitor circuit
- The two outer wafers are identical and are simply the fixed electrodes of the two capacitors



Capacitive Bulk Micromachined Accelerometer

- Holes through the inertial mass reduce the damping effect from air trapped in the enclosed cavity, increasing the operating bandwidth of the sensor
- Measuring range is from ± 0.5G to ± 12G
- Electronic circuits sense changes in capacitance, then convert them into an output voltage between 0 and 5V
- The rated bandwidth is up to 400 Hz for the ± 12G accelerometer
- The cross-axis sensitivity is less than 5% of output
- The shock immunity is 20,000G

Capacitive Surface Micromachined Accelerometer

- Surface micromachining emerged in the late 1980s as low-cost alternative for accelerometers in automotive applications
- Both Bosch company (Germany), and Analog Devices (USA), offer surface micromachined accelerometers,
- The Bosch sensor is incorporated in the Mercedes Benz family of luxury automobiles
- The Analog Devices parts are used on Ford, General Motors, and other vehicles, as well as inside joysticks for computer games

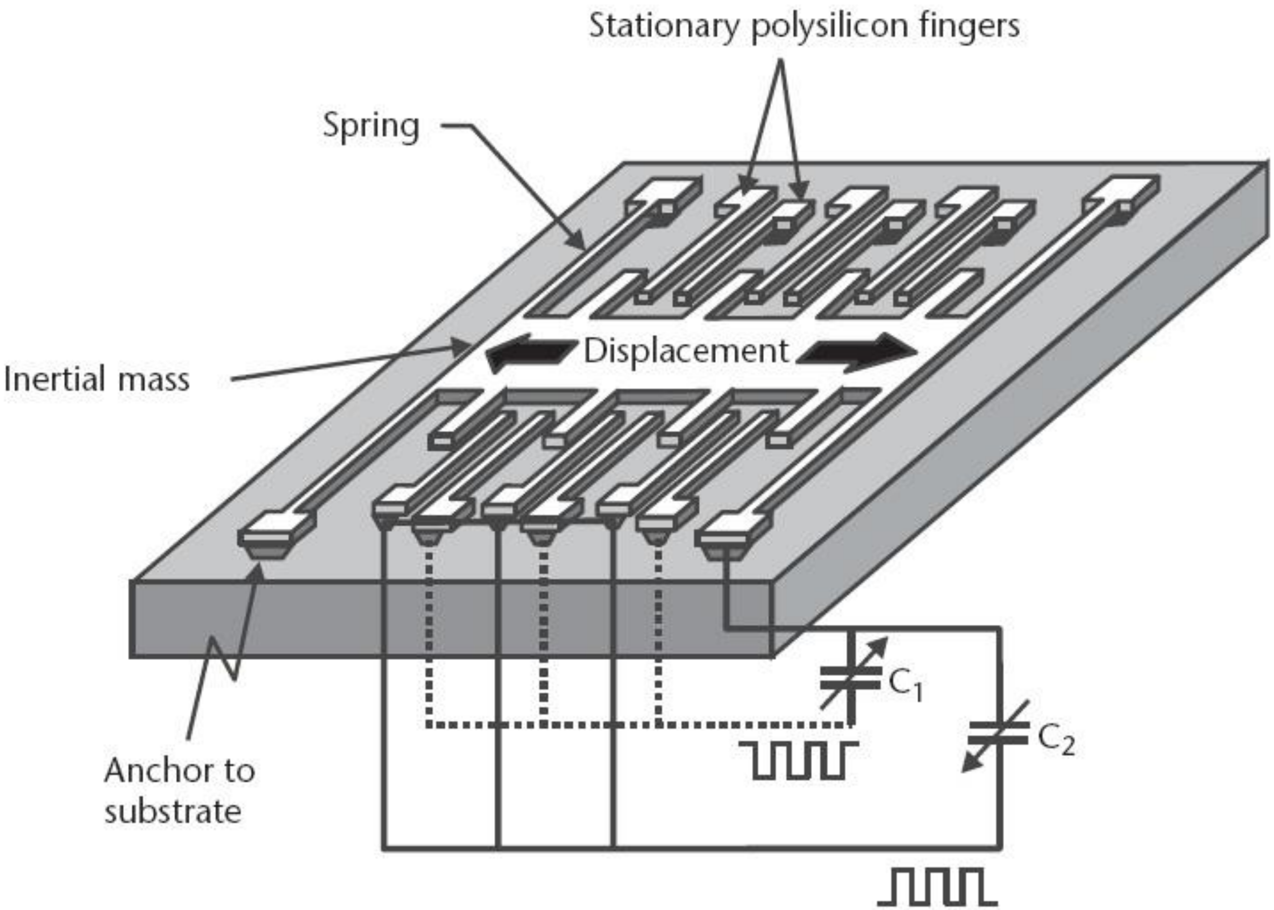
Capacitive Surface Micromachined Accelerometer

- Surface-micromachined accelerometers incorporate a suspended comb-like structure whose primary axis of sensitivity lies in the plane of the die
- This is often referred to as an x-axis (or y-axis) type of device, as opposed to z-axis sensors where the sense axis is orthogonal to the plane of the die
- Surface micromachined accelerometers suffer from sensitivity to accelerations out of the plane of the die (z-axis)
  - Shocks along this direction can cause catastrophic failures

Capacitive Surface Micromachined Accelerometer

- It consists of three sets of 2-μm-thick polysilicon finger-like electrodes
- Two sets are anchored to the substrate and are stationary
  - They form the upper and lower electrode plates of a differential capacitance
- The third set has the appearance of a two-sided comb whose fingers are interlaced with the fingers of the first two sets
- It is suspended approximately 1 μm over the surface by means of two long, folded polysilicon beams acting as suspension springs
  - It also forms the common middle and displaceable electrode for the two capacitors

Capacitive Surface Micromachined Accelerometer



Capacitive Surface Micromachined Accelerometer

- The inertial mass consists of the comb fingers
- Under no externally applied acceleration,
  - The two capacitances are identical
  - The output signal, proportional to the difference in capacitance, is null
- An applied acceleration displaces the suspended structure, resulting in an imbalance in the capacitive half bridge
- The differential structure is such that one capacitance increases, and the other decreases
- The overall capacitance is small, typically on the order of 100 fF (1 fF = 10^{-15} F)
- Programmable ADXL 105 measuring range ±1G or±5G
- ADXL 190 measuring range ±100G
- 1G is converted to 0.1 fF capacitance change
  - This must be measured on-chip to avoid parasitic capacitances of off-chip wires

Random Questions

- Two Random students to ask each other a question

- Left side, second row, third one from the wall

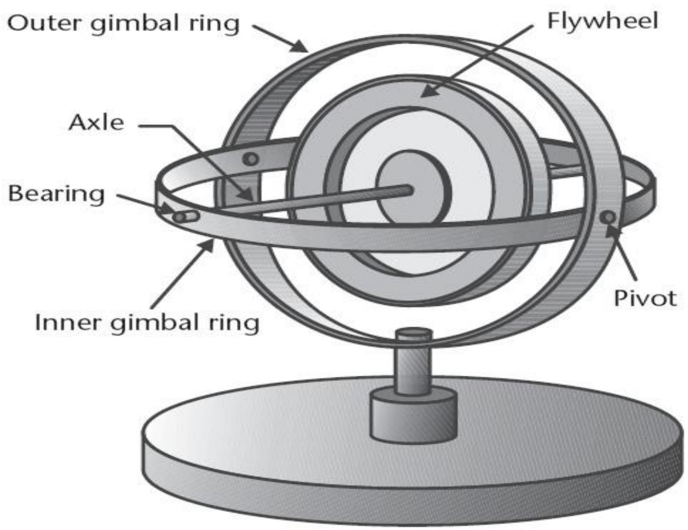
- Right side, last row, second one from the wall

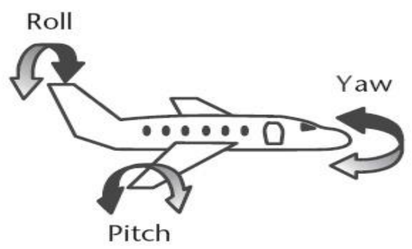
- Punishment:

Choose 3 (other than your GP colleagues) and say their GP topic (Different Groups)

Angular Rate Sensors and Gyroscopes

- The gyroscope maintains a fixed orientation with great accuracy, regardless of Earth rotation
- It consisted of a flywheel mounted in gimbal rings
- The large angular momentum of the flywheel counteracts externally applied torques and keeps the orientation of the spin axis unaltered
- The gyroscope derives its precision from the large angular momentum that is proportional to the heavy mass of the flywheel, its substantial size, and its high rate of spin





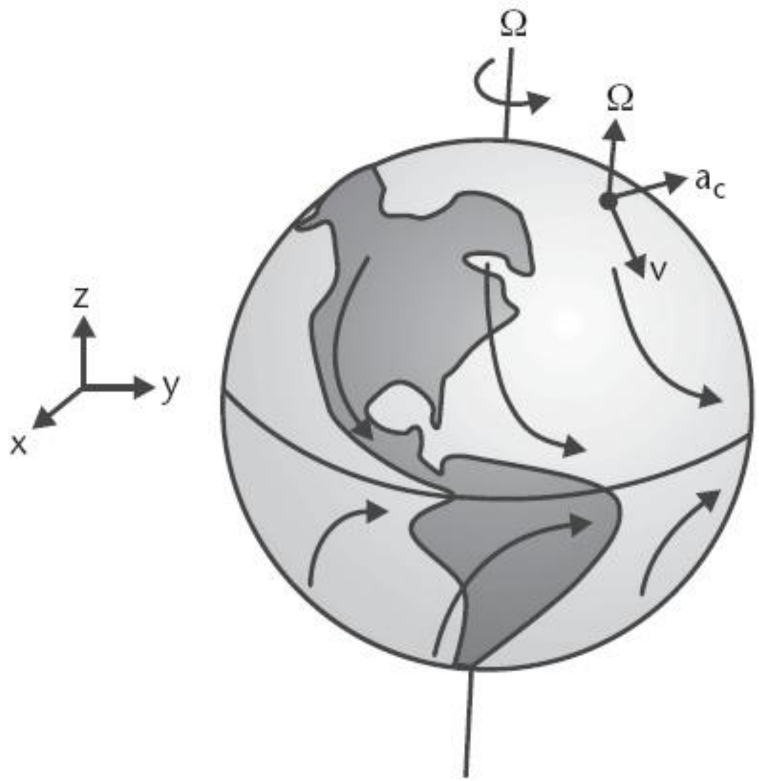
Angular Rate Sensors and Gyroscopes

Angular Rate Sensors and Gyroscopes

- The use of miniature devices is not good to produce useful gyroscopic action because the angular momentum of a miniature flywheel is small
- Instead, micro-machined sensors that detect angular rotation utilize the Coriolis effect
- These devices are angular-rate or yaw-rate sensors, measuring angular velocity, however, they are incorrectly referred to as gyroscopes

Angular Rate Sensors and Gyroscopes

- The Coriolis effect is a direct consequence of a body's motion in a rotating frame of reference

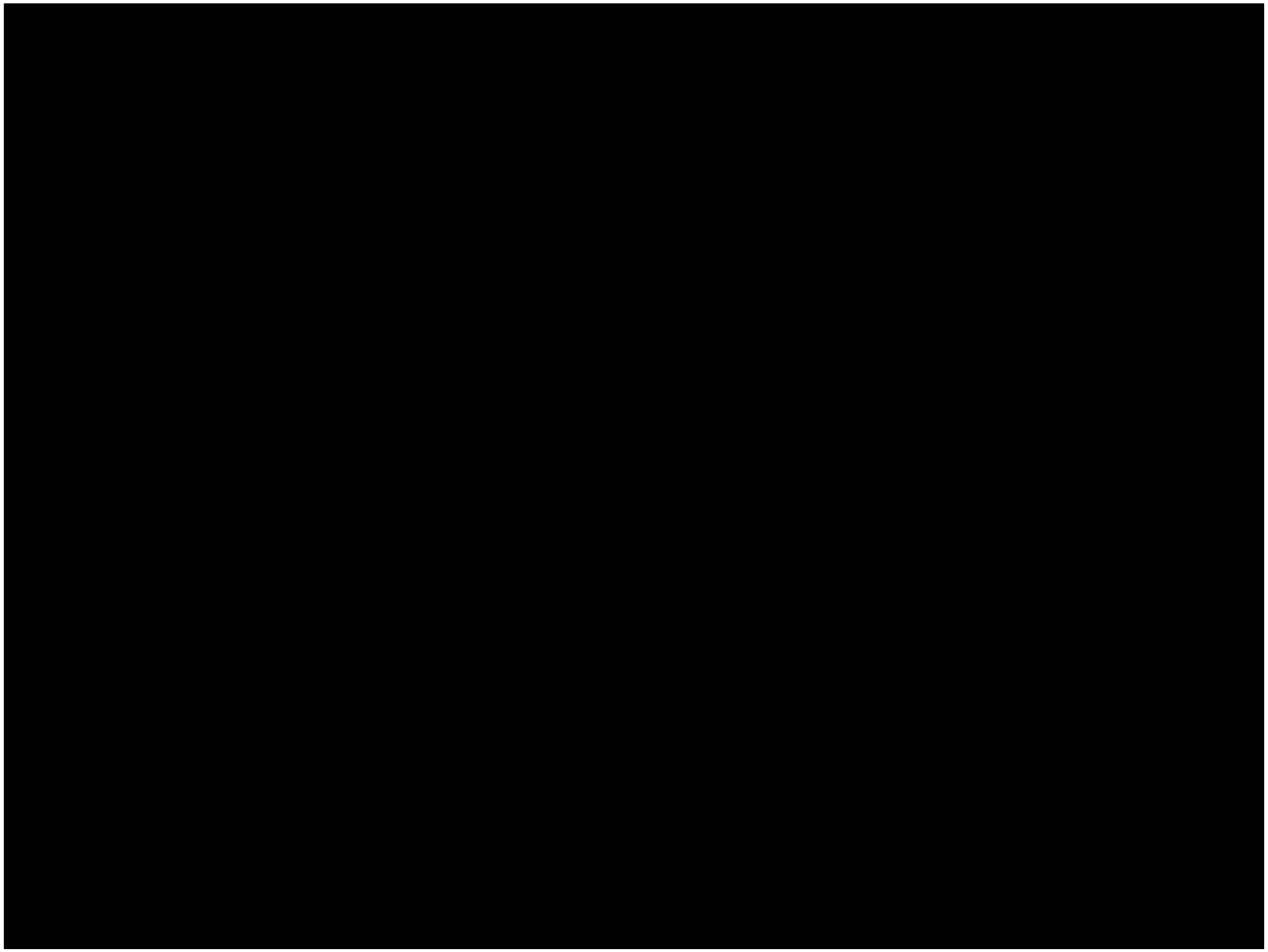


Coriolis acceleration:

$a_c = 2\Omega \times \mathbf{v}$

Angular Rate Sensors and Gyroscopes

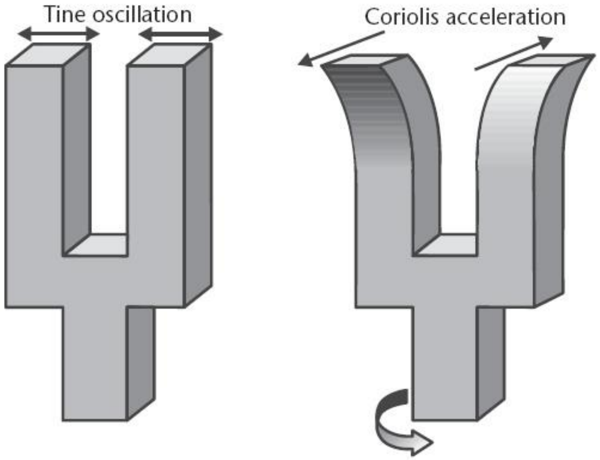
- The Coriolis effect



micromachined angular rate sensors

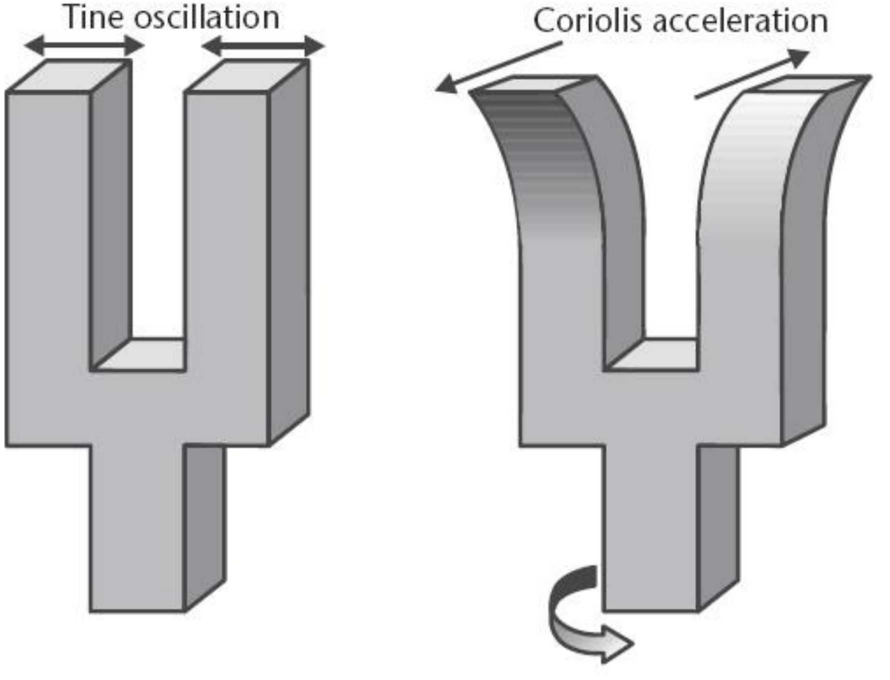
Basic idea

- A vibrating element at their core (the moving body)
- In a fixed frame of reference, a point on this element oscillates with a velocity vector **v**
- If the frame of reference begins to rotate at a rate Ω, this point is then subject to a Coriolis force and a corresponding acceleration equal to $2\Omega \times \mathbf{v}$
- The vector cross operation implies that the Coriolis acceleration and the resulting displacement at that point are perpendicular to the oscillation



micromachined angular rate sensors

- **Basic idea**
  - An energy transfer process from the primary mode of oscillation into the secondary mode that can be measured
  - This excitation of a secondary resonance mode forms the basis of detection using the Coriolis effect



micromachined angular rate sensors

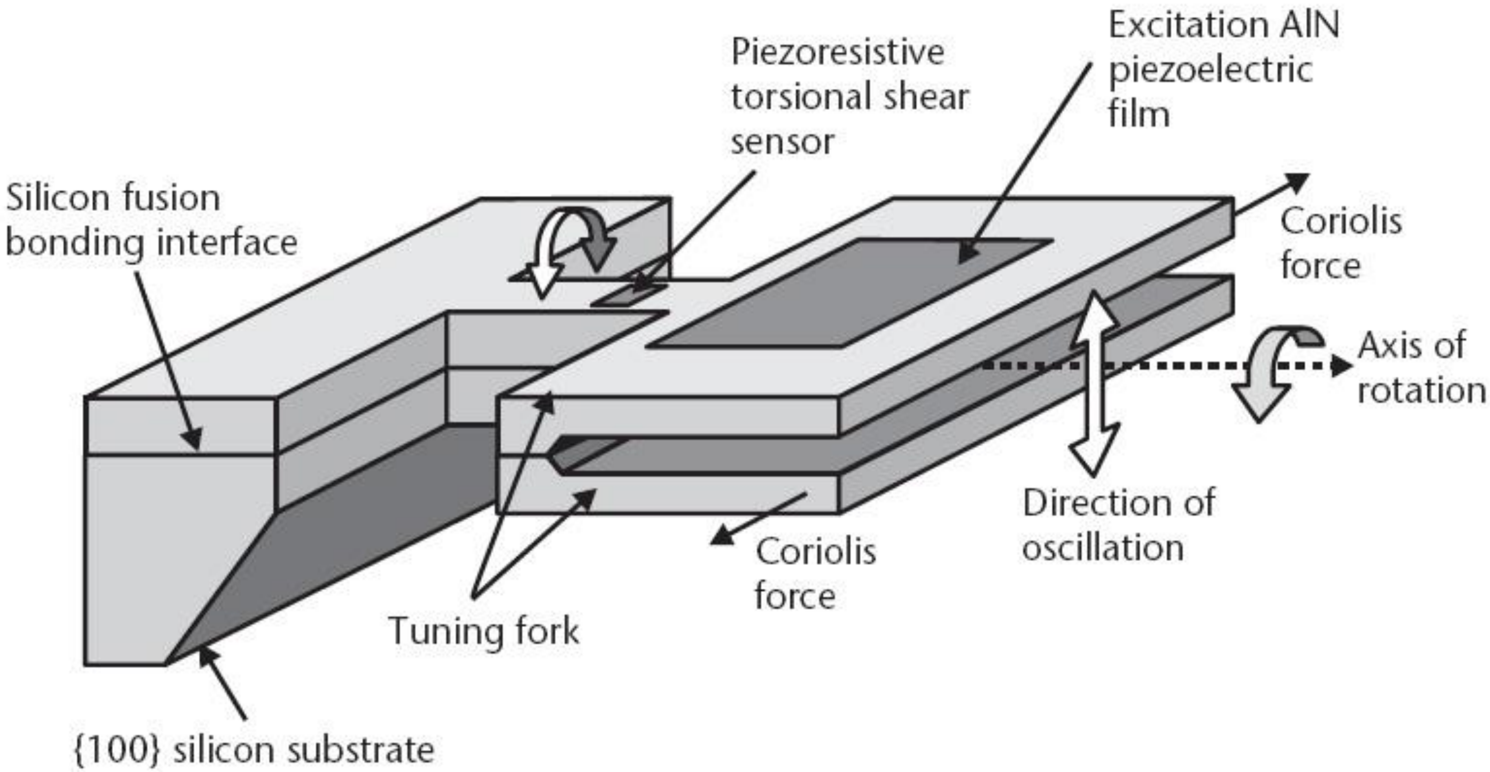
- **Main Specifications:**
  - Full-scale range (expressed in º/s or º/hr)
  - sensitivity [V/(º/s)]
  - Noise, also known as angle random walk[º/(*s· (Hz)*$^{1/2}$*)]*
  - *Bandwidth (Hz)*
  - *Resolution (º/s)*
  - *B*ias (output) drift (expressed in º/s or º/hr)
  - As is the case for most sensors, angular-rate sensors must withstand shocks

Angular-Rate Sensor from Benz

- It is a strict implementation of a tuning fork using micromachining technology
- The tines of the silicon tuning fork vibrate out of the plane of the die, driven by a thin-film piezoelectric actuator on top of one of the tines
- The Coriolis forces on the tines produce a torque around the stem of the tuning fork, giving rise to shear stresses that can be sensed with piezoresistive elements
- The shear stress is maximal on the center line of the stem and corresponds with the optimal location for the piezoresistive sense elements

Angular-Rate Sensor from Benz

- The measured frequency of the primary mode (excitation mode) is 32.2 kHz, whereas the torsional secondary mode (sense mode) was 245 Hz lower



Random Questions

- Two Random students to ask each other a question

- Left side, third last row, second one from the aisle
- Right side, second row, first one from the aisle
  - Punishment:

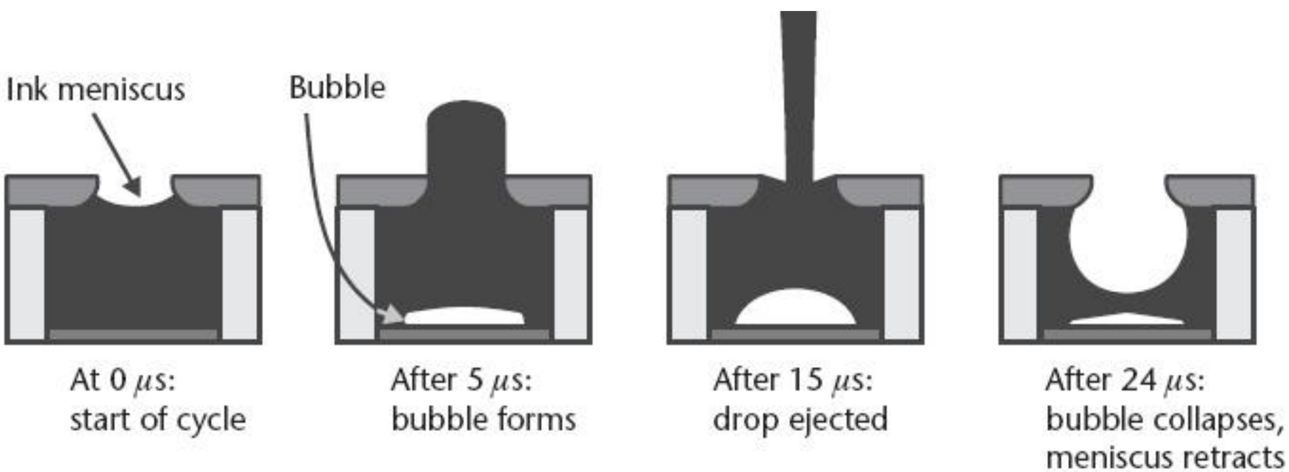
Answer 3 questions (general) asked by your colleagues……

Thermal Inkjet Heads

- Silicon micromachined nozzles provide high resolution in printing
- A resolution of 1200 dots per inch (dpi), the spacing between adjacent nozzles in a linear array is a mere 21 μm
- The device from Hewlett-Packard illustrates the basic principle of thermal inkjet printing

Thermal Inkjet Heads

- A well contains a small volume of ink held in place by surface tension
- To fire a droplet, a thin-film resistor locally superheats the ink beneath an exit nozzle to over 250ºC
- Within 5 µs, a bubble forms and begins to expel ink out
- After 15 µs, the ink droplet is ejected from the nozzle
- Within 24 µs, the tail of the ink droplet separates, and the bubble collapses inside the nozzle
- Within less than 50 µs, the chamber refills, and the ink meniscus settles



Thermal Inkjet Heads

Micromachined Valves

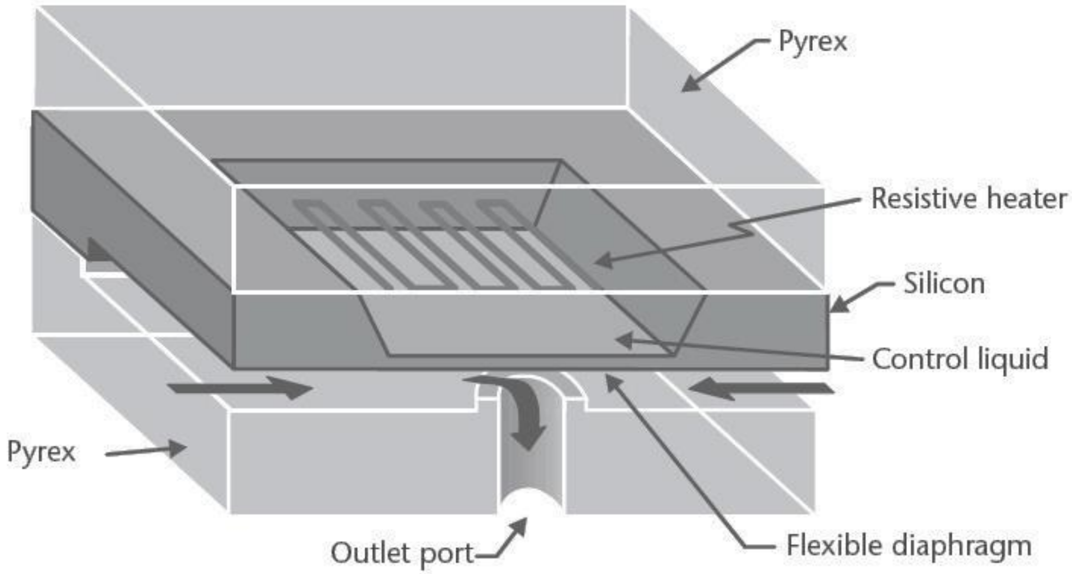
- **Potential applications:**
  - Electronic flow regulation of refrigerant for increased energy savings
  - Electronically programmable gas cooking stoves
  - Electronically programmable pressure regulators for gas cylinders
  - Accurate mass flow controllers for high-purity gas delivery systems
  - Accurate drug delivery systems
  - Control of fluid flow in portable biochemical analysis systems

Fluistor Micromachined Valve

- Fluistor = Fluid transistor
- The actuation mechanism of either normally open or normally closed valves depends on the electrical heating of a control liquid sealed inside a cavity
- When the temperature of the liquid rises, its pressure increases, thus exerting a force on a thin diaphragm wall and flexing it outward
- The Fluistor is either
  - Normally open
  - Normally closed

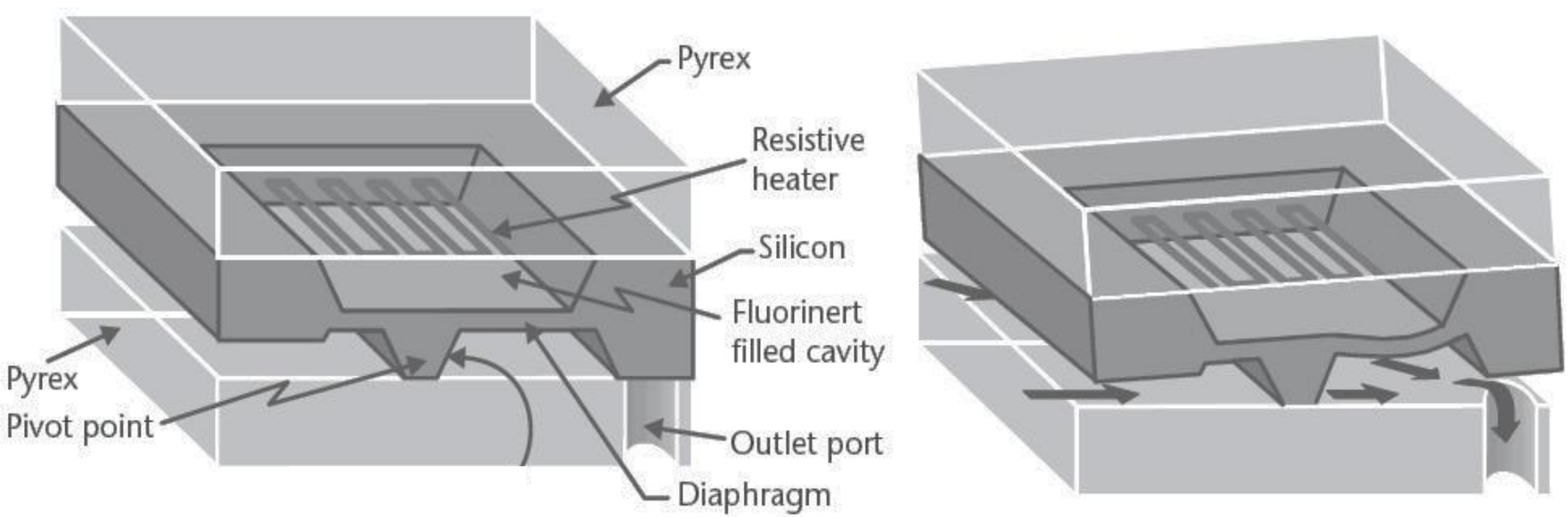
Fluistor Micromachined Valve

- **Normally open Fluistor**
  - In a normally open valve, the diaphragm blocks the fluid flow from the outlet port by its flexing action
  - Upon removal of electrical power, the control liquid entrapped in the sealed cavity cools down, and the diaphragm returns to its flat position, consequently allowing flow through the port
  - The flexing membrane is in intimate contact with the fluid flow, which increases heat loss by conduction and <u>severely restricts</u> the operation of the valve



Fluistor Micromachined Valve

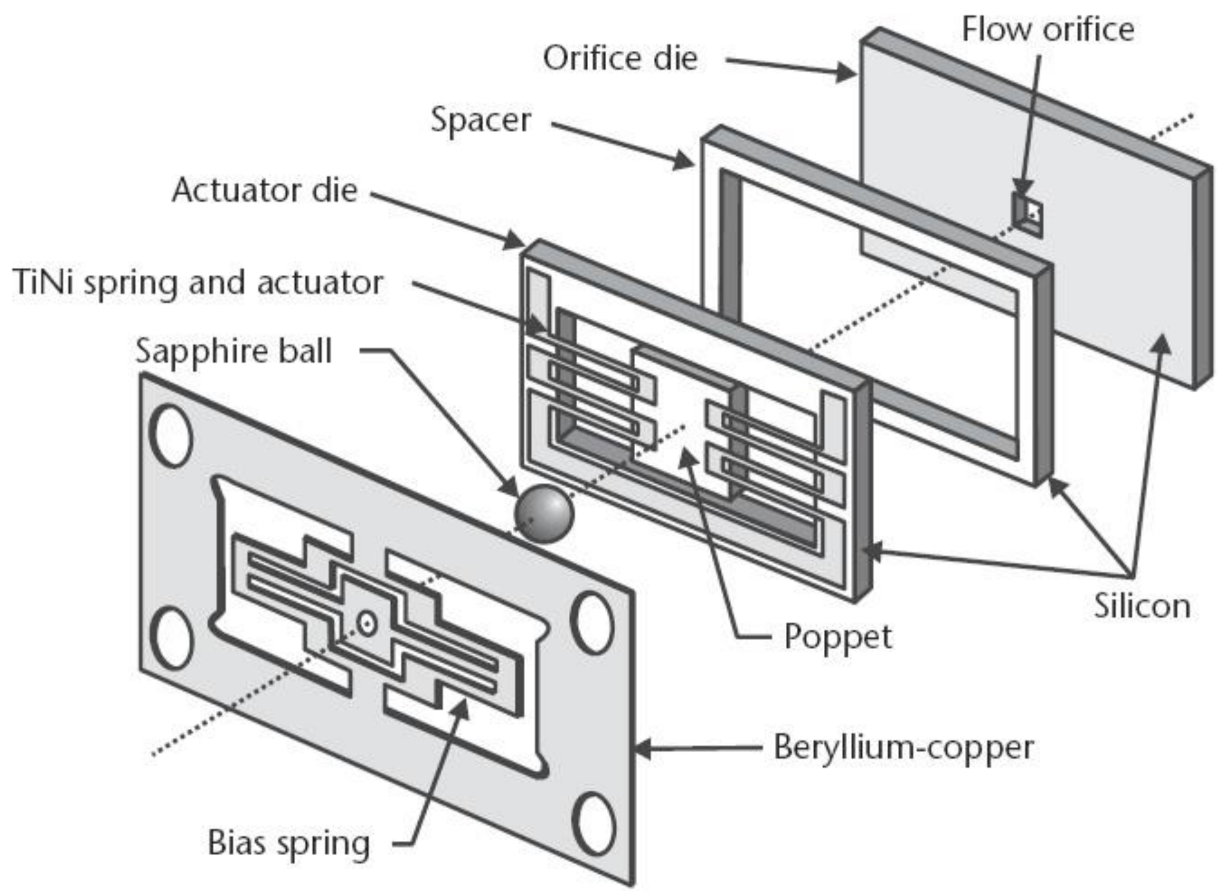
- **Normally closed Fluistor**
  - The normally closed valve uses mechanical levering activated by a liquid-filled thermo pneumatic actuator to open an outlet port
  - The outward flexing action of the diaphragm under the effect of internal pressure develops a torque about a silicon fulcrum
  - Consequently, the upper portion of the valve containing the actuation element lifts the valve plug above the valve seat, permitting flow through the outlet port



Micromachined Valve from TiNi Alloy Company
(Reading and included in the exam)

- Normally closed valve
- The complete valve assembly consists of three silicon wafers and one bias spring to maintain a closing force on the valve poppet
- One silicon wafer incorporates an orifice
- The second wafer is simply a spacer defining the stroke of the poppet as it actuates
- The third silicon wafer contains the valve poppet suspended from a spring structure made of a thin-film titanium nickel (TiNi) alloy
- A ball between the spring and the third silicon wafer pushes the poppet out of the plane of the third wafer through the spacer of the second wafer to close the orifice in the first wafer

Micromachined Valve from TiNi Alloy Company



Micromachined Valve from TiNi Alloy Company

- Current flow through the titanium-nickel alloy heats the spring above its transition temperature (~ 100ºC), causing it to contract and recover its original undeflected position in the plane of the third wafer
- This action pulls the poppet back from the orifice, hence permitting fluid flow

Micromachined Valve from TiNi Alloy Company

- **Micropumps**
  - Micropumps are likely used in the automated handling of fluids for chemical analysis and drug delivery systems
  - The basic structure of the micropump is consisting of four wafers
  - The bottom two wafers define two check valves at the inlet & outlet
  - The top two wafers form the electrostatic actuation unit

reverse direction—hence its bidirectionality. At first glance, it appears that such a

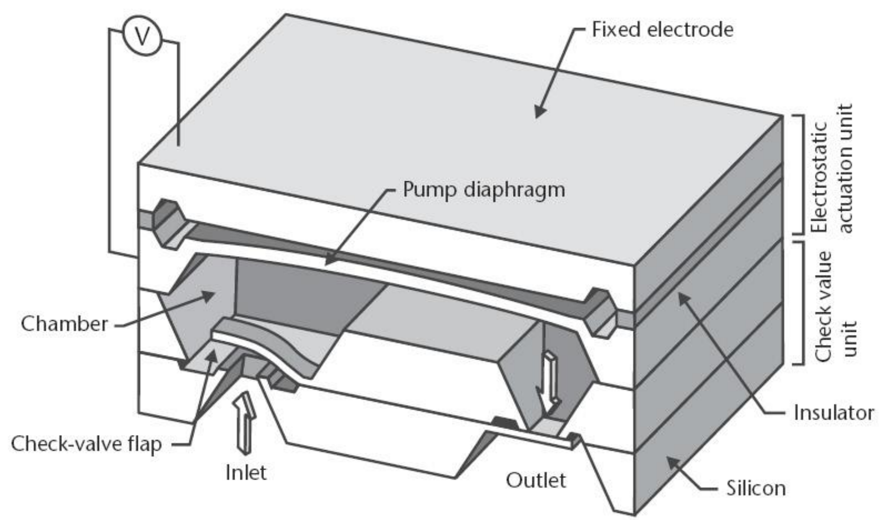


Figure 4.37 Illustration of a cutout of a silicon micropump from the Fraunhofer Institute for Solid State Technology of Munich, Germany [48]. The overall device measures 7 × 7 × 2 mm³. The

Micropumps

- **Micropumps**
  - The application of a voltage between the top two wafers actuates the pump diaphragm, thus expanding the volume of the pump inner chamber
  - This draws liquid through the inlet check valve to fill the additional chamber volume
  - When the applied ac voltage goes through its null point, the diaphragm relaxes and pushes the drawn liquid out through the outlet check valve
  - Each of the check valves comprises a flap that can move only in a single direction:
    - The flap of the inlet check valve moves only as liquid enters to fill the pump inner chamber
    - The opposite is true for the outlet check valve

Random Questions

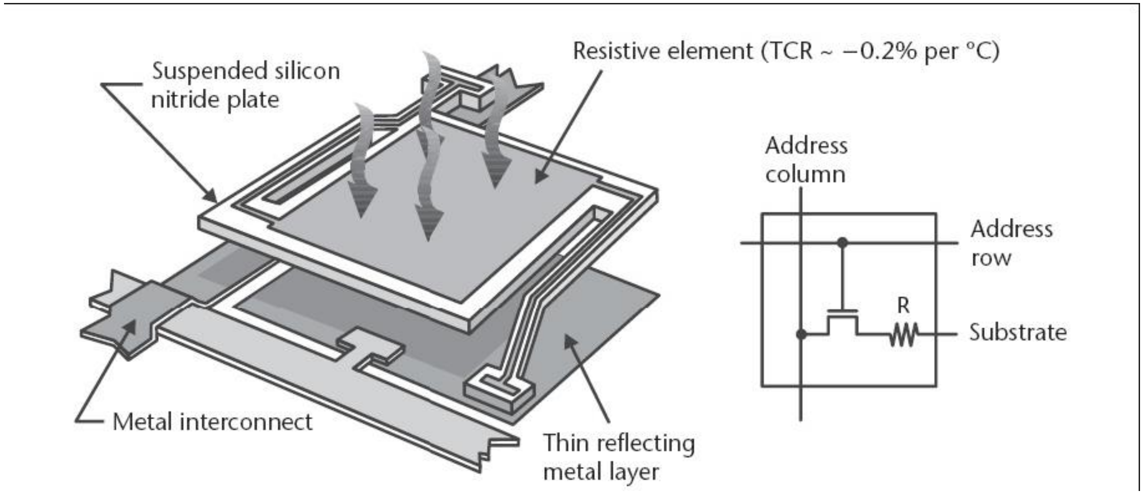
- Two Random students to ask each other a question

- Left side, second last row, second one from the wall
- Right side, second row, first one from the wall
- Punishment:

Turn a round and guess the number of colleagues in your bench. Name of the neighbor one

Infrared Radiation Imager (Sensor)

- It provides high sensitivity to radiation by providing extreme thermal isolation for a temperature-sensitive resistive element
- Incident infrared radiation heats a suspended sense resistor, producing a change in its resistance that is directly proportional to the radiation intensity
- The two-level structure, consisting of an upper silicon nitride plate suspended over a substrate, provides a high degree of thermal isolation

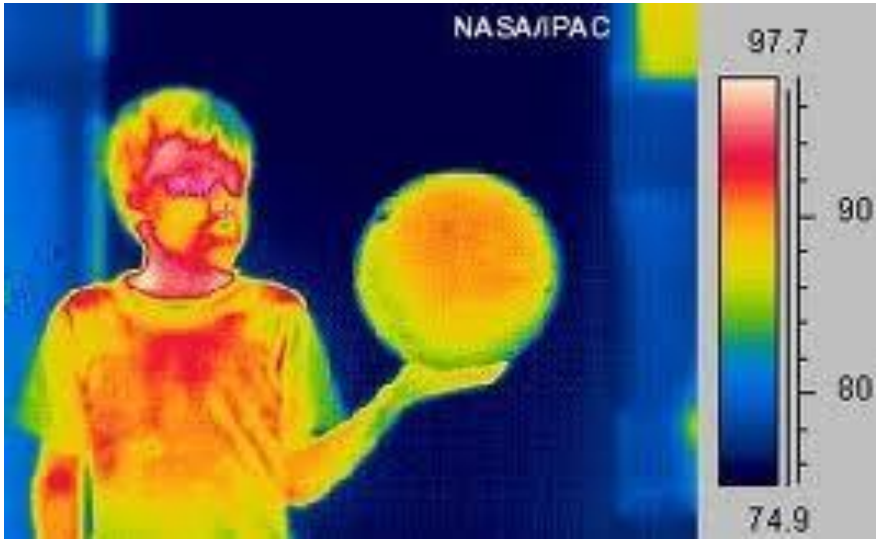


Infrared Radiation Imager (Sensor)

- The thin (~50nm) resistive element rests on the silicon-nitride and has a large temperature coefficient of resistance in the range of −0.2 to −0.3% per degree Celsius
- In order to capture most or all of the incident radiation, the fill factor must approach unity
- Fill factor is the ratio between the area covered by the sensitive resistive element and the overall pixel area
- Surface micromachining process is used
- CMOS electronic circuits are fabricated first on the substrate and then the deposition of the resistive element
- The readout electronics activate a column of pixels by applying a voltage to their corresponding address column, then they measure the current from each transistor

Infrared Radiation Imager (Sensor)

- Calibration:
  - a calibration step that subtracts from the active image the signal of a blank scene
  - The blank scene signal incorporates the effects of non-uniform pixel resistance across the array
  - An intermittent shutter provides the blank scene signal, therefore allowing continuous calibration

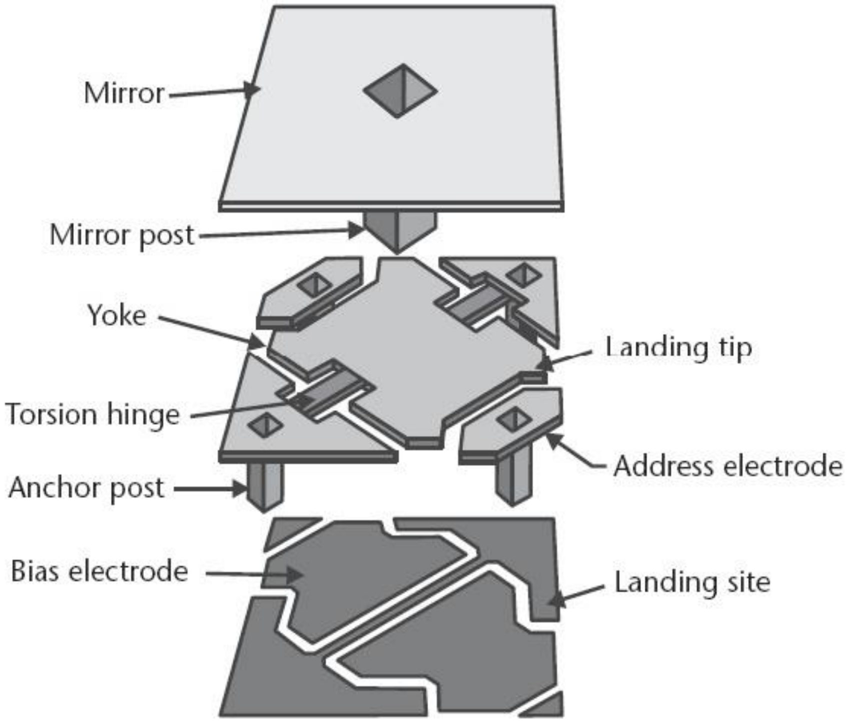


Digital Micromirror Device (DMD)

- DMD has been commercialized by TI in Digital Light Processing (DLP) technology
- DMD consists of a two-dimensional array of optical switching elements (pixels) on a silicon substrate
- Each pixel consists of a reflective micromirror supported from a central post
- This post is mounted on a lower metal platform—the yoke—itself suspended by thin and compliant torsional hinges from two stationary posts anchored directly to the substrate
- Two electrodes positioned underneath the yoke provide electrostatic actuation
- A 24-V bias voltage between one of the electrodes and the yoke tilts the mirror towards that electrode

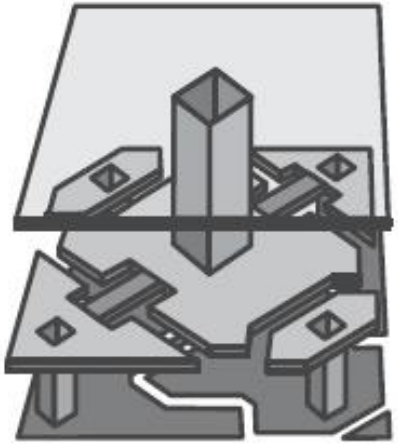
Digital Micromirror Device (DMD)

- The nonlinear electrostatic and restoring mechanical forces make it impossible to accurately control the tilt angle
- Instead, the yoke snaps into a fully deflected position, touching a landing site biased at the same potential to prevent electrical shorting
- The angle of tilt is limited by geometry to ±10º



Digital Micromirror Device (DMD)

- The angle of tilt is limited by geometry to $\pm 10^{o}$
- The restoring torque of the hinges returns the micro-mirror to its initial state once the applied voltage is removed
- CMOS static random-access memory (SRAM) cells fabricated underneath the micro-mirror array control the individual actuation states of each pixel and their duration

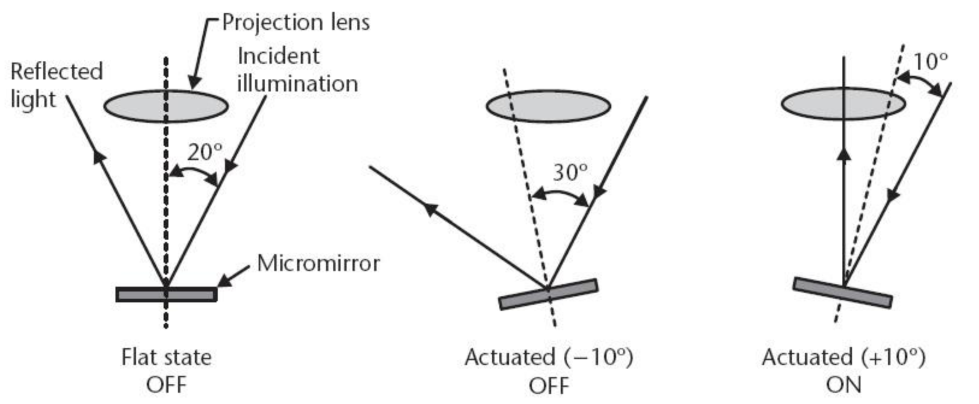


Unactuated state

Actuated state

Digital Micromirror Device (DMD)

- The *OFF state of the memory cell tilts the mirror by* –10º, whereas the *ON state tilts it by +10º*
- In the *ON state, off-axis illumination* reflects from the micro-mirror into the projection lens, causing this particular pixel to appear bright
- In the other two tilt states (0º and –10º), an aperture blocks the reflected light giving the pixel a dark appearance
- This beam-steering approach provides high contrast between the bright and dark states



Digital Micromirror Device (DMD)

- Each micromirror is 16 μm square and is made of aluminum for high reflectivity in the visible range
- The pixels are normally arrayed in two dimensions on a pitch of 14 μm to form displays with standard resolutions
- The fill factor, defined as the ratio of reflective area to total area, is approximately 0.9
- Modulating the duration of the pulse, or the dwell time, gives the eye the sensation of gray by varying the integrated intensity between bright and dark
- The pixel switching speed is 1,000 times faster than the eye's response time → it is possible to fit up to about 1,000 different gray levels (equivalent to 10 bits)

Digital Micromirror Device (DMD)

- Full-color projection
  - uses three DMD chips, one for each primary color (red, green, and blue), with each chip accommodating 8-bit color depth for a total of 16 million discrete colors
    - **$2^8 * 2^8 * 2^8 = 2^{24}$ = 16 Million**
  - OR: uses filters on a color wheel, the three primary colors can be switched and projected using a single DMD chip

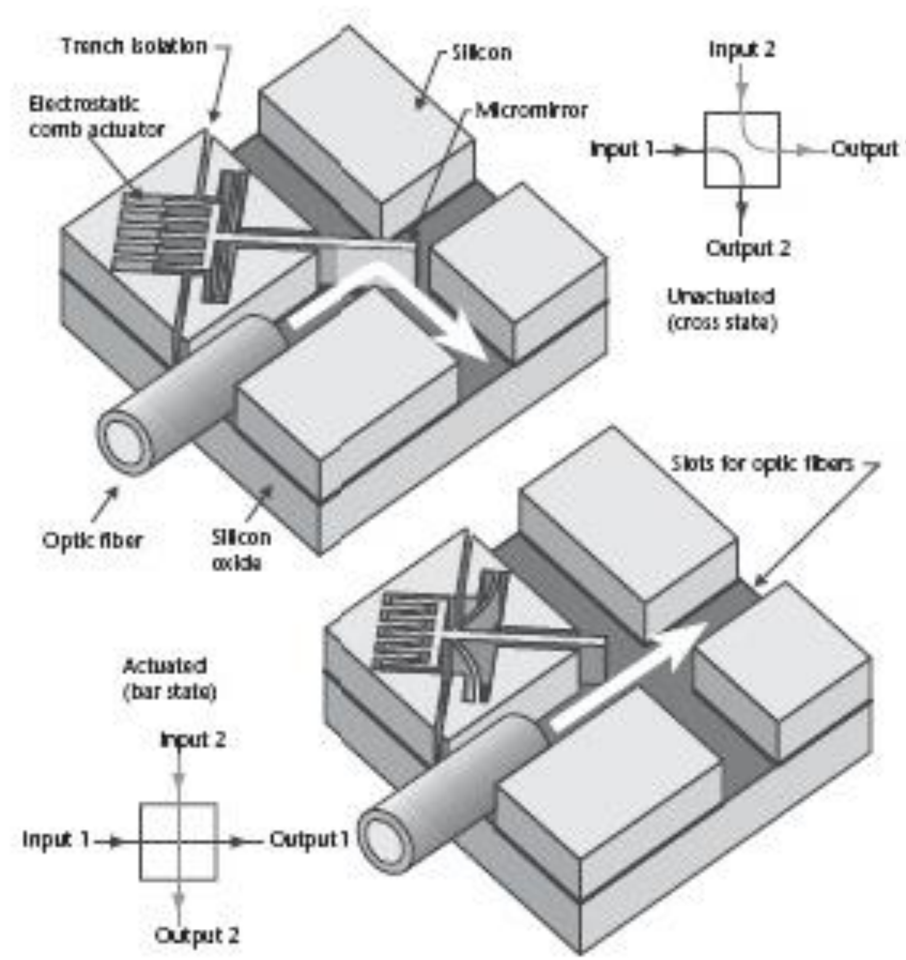
Optical fiber communications (Reading Material included in final exam)

Digital *M × N Optical Switch*

- The basic cell for a 2×2 switch element consists of an electrostatic comb actuator controlling the position of a vertical mirror plate at the intersection of two perpendicular slots
- Within each slot lie two optical fibers, one on each slot end
- In the actuator’s normal unbiased position, the mirror plate sits in the middle of the intersection and reflects the light by 90º, thereby altering the path of data communication—this is the cross state
- Applying approximately 70V to the actuator combs causes the mirror to retract, letting the light pass through unobstructed—this is the bar state

Optical fiber communications

- **Digital *M × N Optical Switch***
  - Arraying the 2 × 2 switch element in both directions creates a generalized *M × N switch matrix*

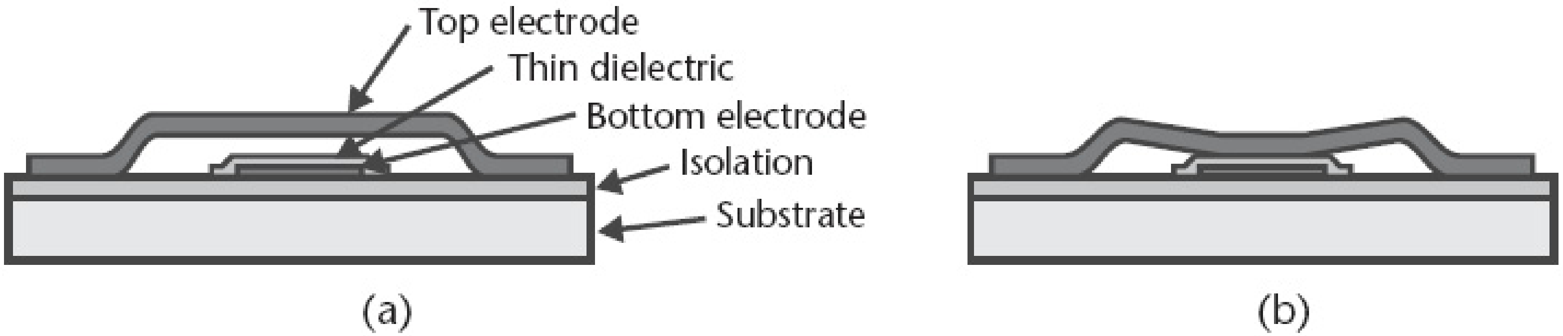


MEMS/NEMS in RF Applications

- **Microelectromechanical Switches**
  - In cellular phones, they can rapidly isolate and connect the send and receive channels to a common antenna
  - The key desirable parameters in RF switches are
    - low insertion loss and return loss (reflection) in the closed state
    - high isolation in the open state
    - high linearity
    - high power-handling capability during switching
    - low operating voltage (for portables)
    - high reliability (particularly a large number of cycles before failure)
    - small size and low cost.

Membrane shunt switch

- 2-μm-thick layer of gold is suspended 2 μm above a 0.8-μm-thick gold signal line, which is coated with about 0.15 μm of insulating silicon nitride
- The membranes have a span of 300 μm and lengths of 20 to 140 μm
- Application of a 15-V dc voltage to the signal line (in addition to the ac signal) pulls the gold membrane down to the nitride, shunting the signal line to ground
- The use of an insulator prevents this switch from working at dc and low frequency



Membrane shunt switch

- **In the closed state,**
  - The connection is made by capacitive coupling, which is only useful at high frequency
  - Insertion loss in the closed state is less than 0.6 dB over the range of 10–40 GHz, with a return loss of less than −20 dB
  - The silicon nitride could be made even thinner for a lower insertion loss, but it is already at the minimum thickness required to prevent breakdown with the required dc operation voltage
- **In the open state,**
  - There is clearly a capacitor that causes undesired coupling
  - The gap could be increased for greater isolation (at least 20 dB is desired), but this would require an even greater actuation voltage
  - The measured ratio of open to closed capacitance in this design is about 17