Introduction to Micro-Optics

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Table des matières

I.Présentation

Module :

Micro-Optics

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Résumé :

This course consists of a descriptive presentation of the history, the main basic concepts and the main manufacturing technologies of optical microsystems.

Mots-clés :

Optical microsystems, Micro-optics, MOEMS

Pré-requis :

Basic knowledge of optics, interference and diffraction.

Objectif(s) pédagogique(s) :

Know the physical concepts, main characteristics and application potential of optical microsystems

Plan du cours :

- Introduction
- Advantages of microsystems
- Origin of optical microsystems
- The main categories of optical microsystems
- Manufacturing techniques and processes
- Characterization of microsystems by optical measurement
- The interaction of light with microstructures
- Bibliography

Conception & production :

Le Mans Université

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II.Lesson

1. Introduction

Micro-Optical-Electro-Mechanical Systems (MOEMS) are micron-sized systems that include both micro-sensors (potentially including optical functions) and micro-actuators. They are thus able to perceive the state of a system and its environment, and to react to modifications of this environment through a control microcircuit. In addition to traditional microelectronics, those systems can also include mechanism-integrated structures, aerials for information exchanges, optical elements and sometimes control systems, power micro-systems, micro-relays, signal processing micro-systems, light sources and sensors. MOEMS✯ and MEMS✯ (from which MOEMS come) thus include mechanisms that are set in motion in a controllable way.

Micro-systems are now enjoying a considerable development, and will continue to do so in the future thanks to their possible applications in various industrial sectors (telecommunications, aeronautics, aerospace, biomedical industry, genetics, automobile manufacturing, home automation, etc.). Their conception and implementation call upon the most fundamental concepts in physics, electronics (components and circuits), micro-electronics, etc. – and the techniques used allow for new functions to be created in mechanics, chemistry, biology, acoustics, fluidics, etc.

A micro-system is a very integrated (and thus hardly observable) and high value-added object. This means that there's a need for a multidisciplinary modeling of various phenomena (mechanical ones, electronic ones, material ones, etc.) in various domains related to micro-systems, in order to guarantee the functionality of the object before it is produced.

The current approach to micro-system conception is based on the definition of various work levels and the necessary links between them. We can see:

- the mathematical/mechanical level, which enables the calculation of structures, thanks to the finite element method,
- the physical model, which will create the structure's architecture,
- the configurable simulation model, integrated in VHDL-AMS language.

Microsystems are obtained by photolithography techniques, which come from microelectronics (cf. part 6).

Their applications are more extensive than only micro-electronics: mechanics, electromagnetism, quantum physics, thermics, biochip, lab-on-a-chip, optics, new sensors, etc.

Définition : Microsystems

Combination of sensors, actuators, and possibly associated circuits, ideally integrated in order to complete more or less complex tasks.

A micro-system converts a physical input signal (radiation, thermic signal, magnetic signal, mechanic signal, etc.) or chemical (concentration, etc.) into an electrical signal that will then be treated and transformed into the desired exploitable format.

So, we talk about **MEMS**✯: **Micro-Electro-Mechanical Systems**

- Micro: micron-sized
- Electro: use of circuits and electrical devices,
- Mechanical: use of mechanical structures and devices

Well-known MEMS applications: airbag accelerometers, inkjet printer heads, read/write heads for magnetic storage devices, etc.

Then about **MOEMS**✯: **Micro-Opto-Electro-Mechanical Systems**

or: **Optical- MEMS**

- Opto or optical: combination of the previous elements with optical devices and phenomenon.

They are micro-systems whose applications and components are essentially based on optics or photonics, with well-known applications: mirrors, switches, connectors, optical modulators, wavelength-division multiplexing (WDM) and demultiplexing (DWDM) devices, etc. With an aim to obtain smart sensors and actuators with added features such as self-test and self-calibration.

The goal of this course is to be an introduction to the origins and main characteristics of optical micro-systems. The main production techniques will also be presented.

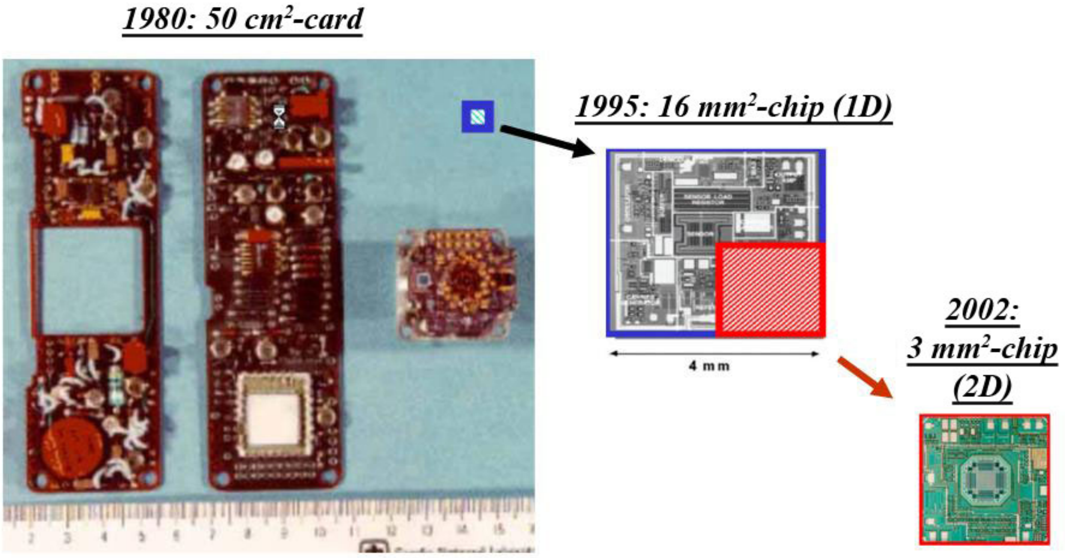
2. The advantages of micro-systems

The question is: why do we want to miniaturize things?

To reduce bulk...

Exemple

We can compare the size of a 1980 airbag accelerometer ($50cm^2$-card) with the 1995 one ($16mm^2$-chip) and finally the 2002 one ($3mm^2$-chip).



But not only ...

- MOEMS✯ require very light mechanical forces,
- optical phenomenon require very small displacements $-\lambda/4$,
- MOEMS are compatible with integrated circuits, particularly thanks to the use of silicon,
- miniaturization makes it possible to integrate source detection, data processing and conditioning on a same chip that is compatible with integrated circuits; miniaturization makes it possible to develop sensor or detector networks,
- the small distance between elements helps reduce capacitive effects, and the use of optical wavelengths helps reduce the response time and broaden bandwidths,
- there is a reduction of production costs: it is less expensive to use micro-electronics technologies for mass production (using a single wafer), to integrate various functions onto a single chip and to reproduce a device by the millions for a cheaper cost,
- mechanical resistance is augmented by the use of very high resonant frequencies and, in most cases, of silicon single-crystal.

There are, however, disadvantages:

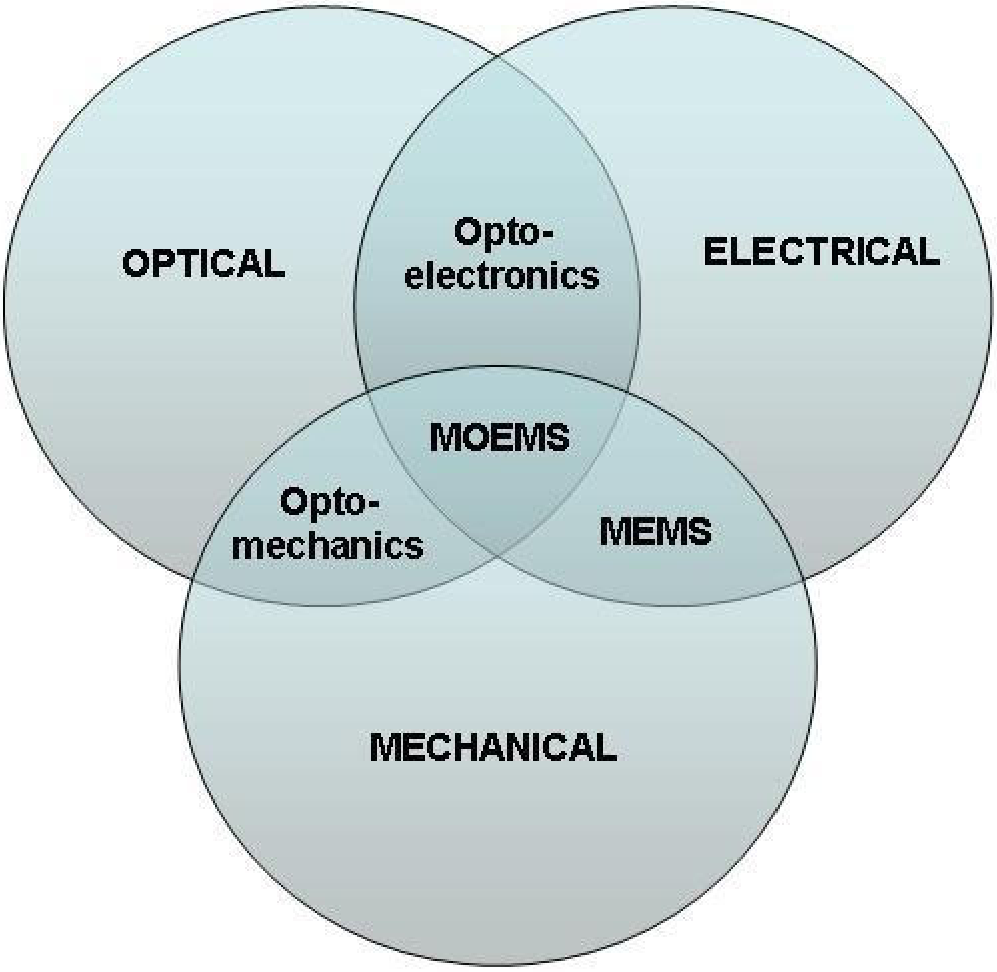
- the noise and noise amplification problems,
- the very high development costs,
- the physical limits to further miniaturization.

3. Origins of optical micro-systems

Introduction

Optical micro-systems are at the crossroads of three main domains:

- micro-mechanics,
- micro-electronics,
- optics/photonics.



Micro-mechanics is a very old science. It dates back to the 14th century. It comes from the watchmaking industry and its need for miniaturization in order to make time pieces (creation of micro-gears and micro-actuators). But extreme miniaturization creates more and more problems, like for example:

- is the mechanics theory still valid?
- inertia: with very low masses, components are put into motion almost instantly,
- electrostatic forces win over magnetic effects, whereas at macroscopic level it is the opposite,
- compensation of temperature variations.

The production of micro-machines is based on the construction of micro-mechanical structures thanks to etching processes that take off part of the substrate or of thin layers. It gets immediately more complicated when you need to create devices with structural lattices.

Silicon (Si✯) is an exceptional material for these micro-structures. Its mass density is very high: $2,4.10^3 kg.m^{-3}$ and so is its Young's modulus ($1,3$ to $1,7.10^{11} Pa$). We will see below that those characteristics are essential to micro-mechanical design, will ally with the micro-electronic ones.

Important dates:

- 1962: first high-sensibility silicon membrane, to make a pressure sensor,
- 1970: isotropic etching of silicon following its crystallographic orientation, in order to create those membranes,
- 1976: anisotropic etching,
- 1980: first MEMS✯;
- 1990: diversification of those devices to the fields of chemistry, biology, micro-fluidics and biomedicine.

There have been what we could call four revolutions in techniques.

First revolution: micro-electronics

It was the first and most important. During the second part of the 30s, the Telephone Bell laboratory wanted to replace mechanical switches in phones with electronic switches. Two semiconductor materials were then mainly used: Silicon (Si✯) and Germanium (Ge✯) with a band gap of $1,11eV$ and $0,67eV$ respectively.

Silicon revolutionized technology with integrated circuits, thanks to its higher band gap. However, Germanium wasn't abandoned because it is transparent to the wavelengths used in telecommunications (around 1550 nm) and Silicon isn't.

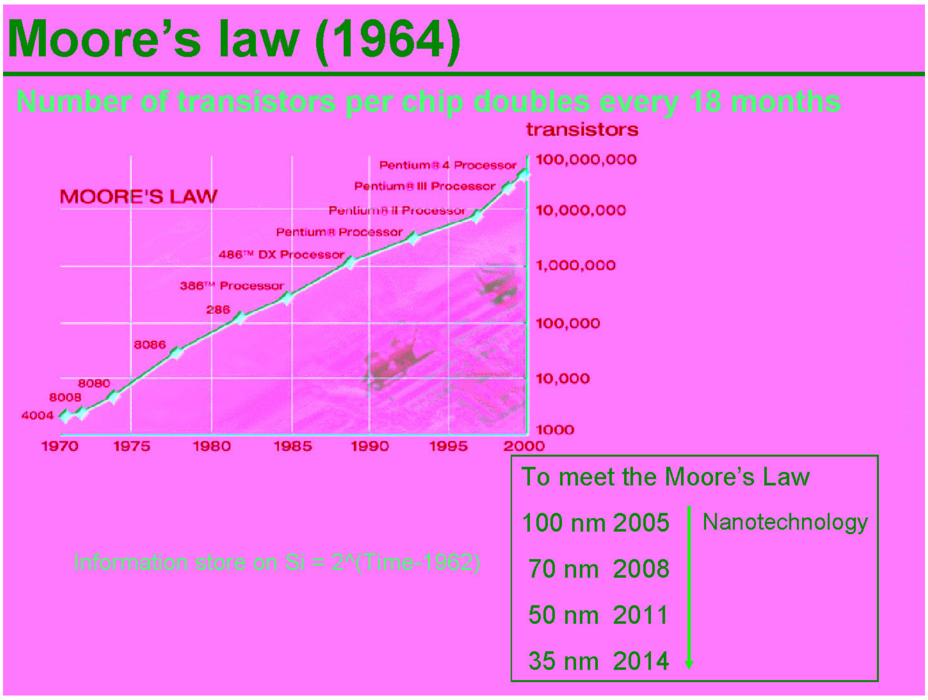
Three discoveries made this revolution possible:

- the discovery of the Transistor - for transfer resistor - semiconductor materials in 1947 by William Schockeley, Walter Brattain and John Bardeen (Nobel Prize, 1956),
- the development of the planar transistor technique by Bob Noyce (co-founder of Intel) in 1959,
- the first integrated circuit (IC✯) by Jack Kilby at Texas Instruments in 1959 (Nobel Prize, 2000).

Again in 1959, Bell came out with the first *Metal Oxyde Silicon* transistor (MOS✯) in opposition to bipolar technologies. It is an integrated version of a transistor.

In 1960, the industrial production of integrated circuits started in Japan with Hitashi and Toshiba, and in the USA with Motorola.

In 1965, Gordon Moore noted that the number of integrated transistors on a Silicon small plate was doubling every year, a rate soon reduced to every 18 months. He then described what would become Moore's Law, which predicts that the medium size of a transistor would fall to $100nm$ in 2005 and reach $35nm$ in 2014.



Moore's law (1964)

Number of transistors per chip doubles every 18 months

Information store on Si = 2^(Time-1962)

To meet the Moore's Law

100 nm 2005 Nanotechnology
70 nm 2008
50 nm 2011
35 nm 2014

Such an evolution won't continue forever, because if components reach the atomic size, physical laws will change and our technologies won't be useful any more.

At this point, there is no known replacement for Silicon.

Second revolution: RF and wireless technologies

Communications became wireless and portable.

Wireless technology dates back to 1901 and Marconi's work on radiofrequencies (RF✯) for which he got the Nobel Prize in 1908, but the development of wireless technologies is much more recent.

Those devices require very small dimensions and very low production costs.

Third revolution: photonics

Photonics is linked to the development of telecommunications by optical fiber.

In 1970, the Corning Glass company created the first highly-transparent fibers. At the same time, Bell Labs put the last touch to the first semiconductor laser that could function at room temperature.

It then became apparent that there was no better material for those applications that optical fiber and that light would be the best signal source.

Photonics were born. It presented the very interesting capacity to transmit different luminous wavelengths at the same time in the same fiber: it is called multiplexing (WDM✯ or DWDM) for « *Wavelength Division Multiplexing* ».

In 2002, a standard light source was able to emit 10^{16} photons per second, a sensor to measure 1 bit of only 10 photons at a speed of 10^{15} bits/s through a single optical fiber, and it was possible to process 64 multiplexed channels.

Fourth revolution: MEMS

MEMS✯ are seen as the next step in the micro-electronic revolution, and many researchers are convinced that they are going to become as common place as microprocessors.

Nowadays, they make possible the construction of systems that integrate either:

- an actuation function (micro-engine) or

- a detection function (micro-sensor).

To produce:

- Inkjet printer heads,
- Gyroscopes,
- Micro-engines,
- Micro-pumps,
- Optical micro-benches,
- Alignment benches for micro-mirrors,
- Optical switches,
- Bolometers,
- Biochips for DNA sequencing,
- etc

The development of micro-electronics followed Moore's Law: "*smaller is better* " and systems were designed by connecting universal generic elementary blocs (transistors) for different applications. It doesn't work for MEMS✯, though, because the notion of generic elementary blocs doesn't exist.

What about optics?

Photonic devices tend to integrate very naturally with MEMS✯ because micro-manufacturing technologies are already present in integrated optics.

Examples:

- LED, laser diode, laser,
- Optical fiber,
- Integrated wave guide, modulator for telecommunications,
- Mirrors, diffraction networks, etc.
- ...

Integrated optic components are on a micrometer scale because optical wavelenghts required the use of visible and near infrared domains.

Theoretical tools are also available on this scale (scalar diffraction).

4. Main categories of optical micro-systems

MOEMS✯ can be divided into two main categories:

- components working according to geometrical optic principles for the spatial displacement of light (connectors, switches, etc.),
- components that allow us to manipulate optical interferences (modulators, networks, etc.).

In MOEMS✯, light propagate exclusively in the air. However, a new trend seems to associate optical micro-systems with integrated optics, so as to make part of the light propagate inside wave guides.

The main categories can be found in the following list:

- Sources,
- Optical wave guides,
- Free Space Optics,
- Transmission-aimed optics,
- Optical mirrors,
- Diffractive optics,

- Interferometric optics,
- Sensors.

Complément

Those categories will be developed further in the summary “Applications of Micro-optics”.

5. Manufacturing techniques and processes

Materials used for micro-manufacturing

Single-crystal Silicon is the material most often used in micro-manufacturing for various reasons (see next part: “characteristics of Silicon”).

Germanium isn't a viable alternative for this kind of applications. Indeed, its native oxide GeO_2 is soluble in water, which makes it unusable for photolithography.

Glass is a material especially interesting for the chemical or biological uses of optical systems.

The micro-manufacturing principles below can, for the most part, be applied to glasses.

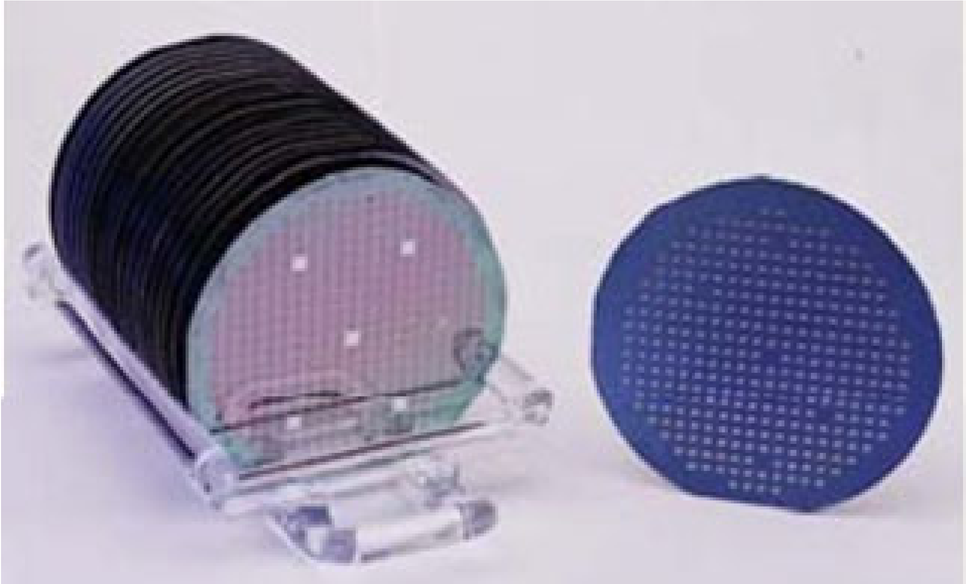
Other materials are used for micro-fabrication: mostly polymers, metals and semiconductors III-V (AsGA, InP, etc.).

Silicon characteristics

Why use silicon?

- Availability of the material and considerable knowledge of its properties;
- Very high purity (single crystal);
- Various established micro-manufacturing processes that make it possible to create devices easily on a sub-micrometer scale;
- Anisotropic properties, useful for micro-manufacturing;
- Possibility to integrate sensor and actuator functions to associated electronic circuits;
- Physical and chemical characteristics compatible with a great number of processes;
- Highly piezoresistive (useful to realize deformations);
- Very good mechanical properties compared to metals (good resistance to mechanical fatigue, reproducible elastic properties, no plastic zone, etc.);
- The technology of Silicon captors is identical to the one used to create integrated circuits (miniaturization, mass manufacturing, existing infrastructures, etc.).

Silicon is available in the form of wafers that are almost only a single-crystal.

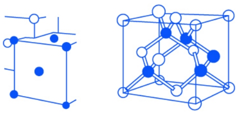


Silicon is produced by a controlled crystal growth process that takes place in a very clean environment of class 1 or 10 (see next paragraph: “Environment for micro-manufacturing”).

The growth process consists in slowly drawing a crystal from an ultra-pure silicon bath in rotation.

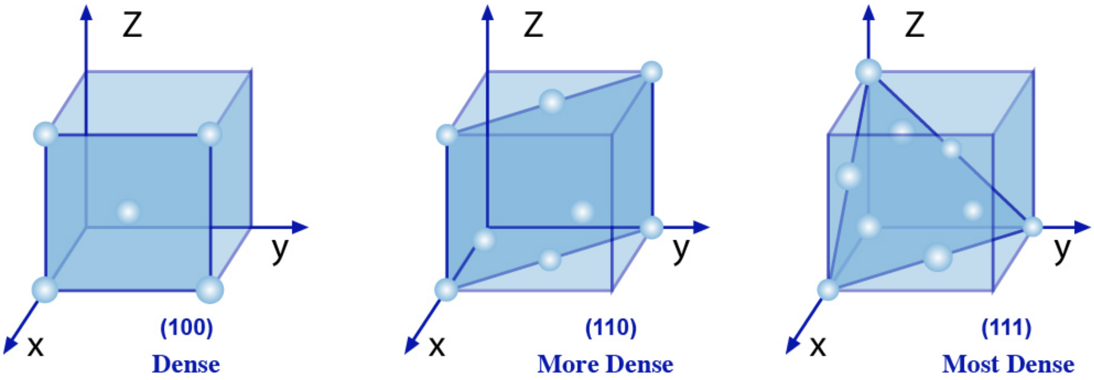
Wafers are cut off from the cylindrical crystal obtained, with a thickness of a few hundred microns. Then an atomic polishing process takes place, so as to create a small plate with an almost atomically smooth surface on the polished faces, and with a crystallographic orientation identified by two planes.

From a crystallographic point of view, Silicon is a cubic crystal with a structure akin to diamond and in which two interlocked face-centered cubic lattices can be identified. Each tetravalent Silicon atom belonging to a given network is at the center of a tetrahedron.



The network's mesh is about $54.3nm$.

The higher density planes are the (111) ones. They form an angle equaling 54.74 degrees compared to the (100) planes.



Adapted from: S.M. Sze, Semiconductors devices

There are also the particular cases of multilayer wafers Si-SiO_2 better known as SOI✯ (*Silicon On Insulator*) wafers.

Environment for micro-manufacturing

Given the dimensions of the objects involved, the environment must be very clean. Indeed, a "standard" dust is of micrometric size and tends to adsorb on surfaces.

Définition : What is a cleanroom ?

A cleanroom is a work environment where temperature and hygrometry are controlled (the temperature is $20^\circ C$). Filtered air in light overpressure constantly flows through the cleanroom, so as to constantly eliminate dust and gases that could enter the room.

A cleanroom is identified by its class, which represents the number of dust particles whose size is under $4 \mu m$ that are contained in a cubic inch (one inch = $2.56 cm$).

Standard class for MEMS✯: 1000-10000

Standard class for micro-electronics: 1-10

Class	Maximum number of specks by cubic inch of air, whose size is superior or equal to the sizes below					Typical applications
	0.1 µm	0.2 µm	0.3 µm	0.5 µm	5 µm	
1	35	7.5	3	1		Integrated circuits
10	350	75	30	10		
100		7502	300	100		Microball-marking; photo labs; medical implants
1000				1000	7	
10000				10000	70	Color ray tubes; surgical units
100000				100000	700	Ball marking

Photolithography and masking

Photolithography is the first key process in micro-manufacturing.

It consists in insulating of a photoresist (polymer) through a mask that was previously laid on a substrate so as to "draw" a structure or a structure element.

Lithography techniques can be divided in families according to the wavelength of the light source used

- X-rays source
- Electron beam
- Ion beam
- UV, infrared or visible light source

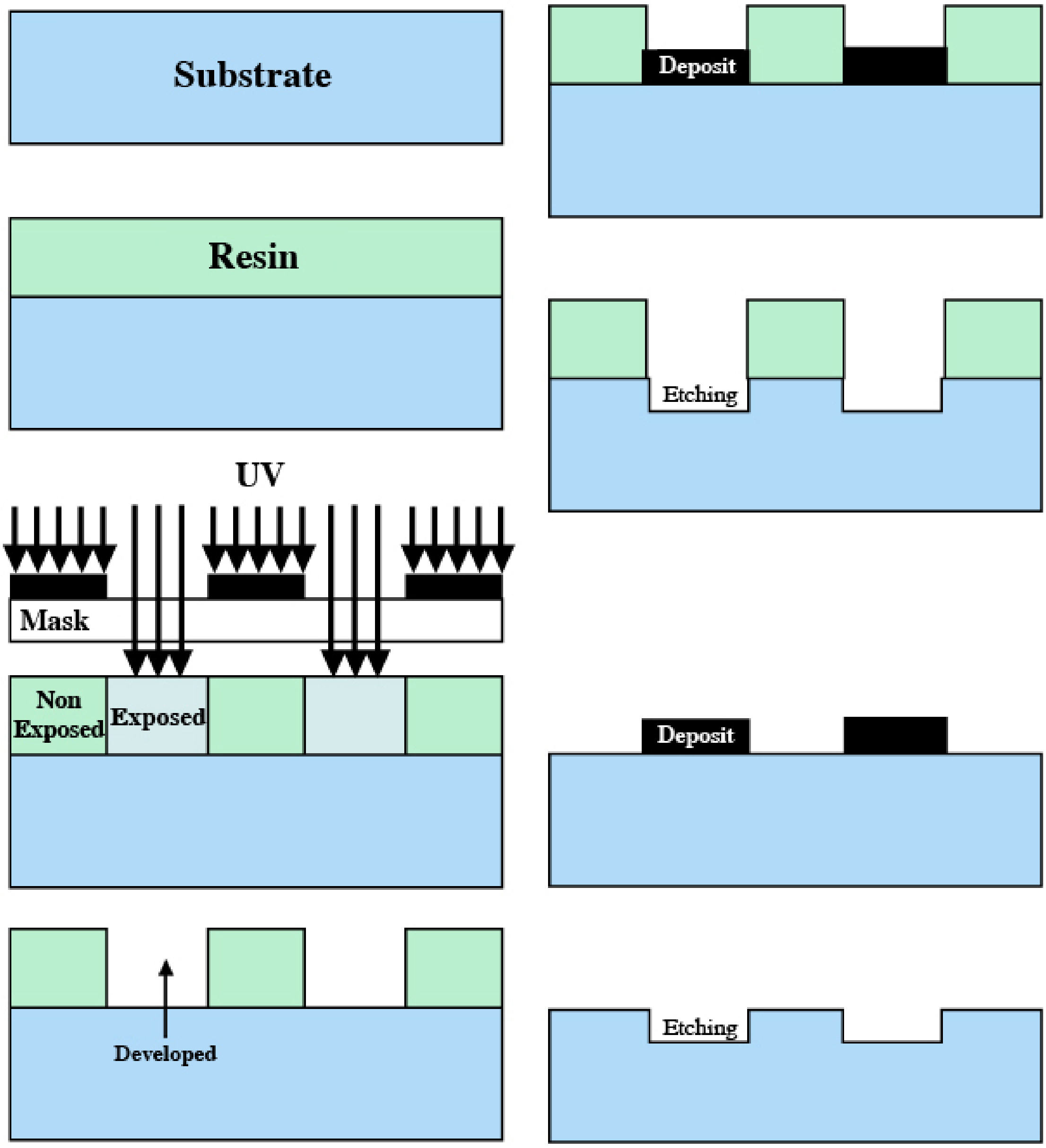
Obviously, the lower the wavelength is, the higher the accuracy.

The masks used are generally quartz plates on which a Chromium pattern was deposited, in most case by using an electron beam, with accuracy on a scale of a fraction of a micron.

It seems it is not possible to manufacture an object with a geometrical accuracy higher than that of the mask.

Photolithography comprises five steps:

- Step n°1: preparation of the wafer. It's a cleaning phase essential to eliminate dust and impurities on the surface.
- Step n°2: deposit of a thin film of resin (usually $2\mu m$) by spin coating (tournette).
- Step n°3: insulating through a mask. This step requires the use of a mask-liner.
- Step n°4: developing of the insulated photoresist polymer with a solvent.
- Step n°5: polymerization of the resin by heating the system to a temperature higher than the glass transition for about 10 minutes.



Two types of resins are used according to the result wanted:

- "positive" resisn: the developing step leads to the elimination of the resist insulated through the mask, revealing openings towards the substrate that draw the structures in negative,
- "negative" resin: the developing step leads to the elimination of the non-insulated resist, leaving the polymerized resist on the substrate to draw the structures in positive.

Photolithography is thus about delineating active areas in the photoresist polymer so as to create openings on the substrate. The other areas are used as protection layers for the substrate during the etching process.

Photoresists must possess the following characteristics:

- High solubility contrast between the insulated and non-insulated areas;
- High photosensibility in order to absorb the rays;
- Good resistance to some types of chemical agents.

Examples of resins:

- "Positive" resins: PMMA, DQN, AZ-1350, etc. Those resists are soluble in highly alkaline solutions like potassium hydroxide or acetates.
- "Negative" resins: KTFR, SU8 –the last one is fairly recent (IBM, 10 years ago) and makes it possible to have high aspect ratio structures for thick deposit layers and high photosensibility.

IC-technologies transfer to micromachining

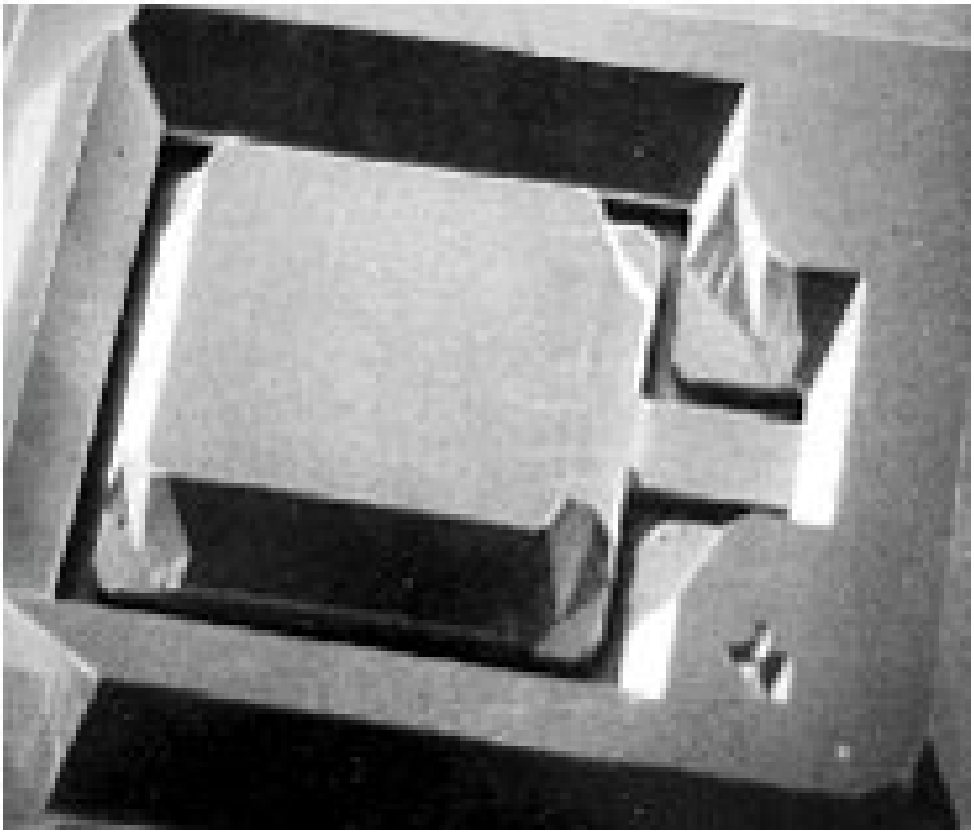
To create a micro-system from a simple wafer, it is necessary to add or remove matter so as to create a 2D or 3D structure. To do this it is necessary to give deposit additional layers or carry out more etching steps of the Silicon on glass substrate.

"Integrated circuit" processes	**"Micro-system" processes**
Oxidation	Surface micromachining
Diffusion	(Dry or wet) volume micromachining
LPCVD	Wafer welding
Photolithography	Casting
Epitaxy	Double faced photolithography
Evaporation	Specific active materials (shape memory alloys, piézoélectriques, ...)
...	...

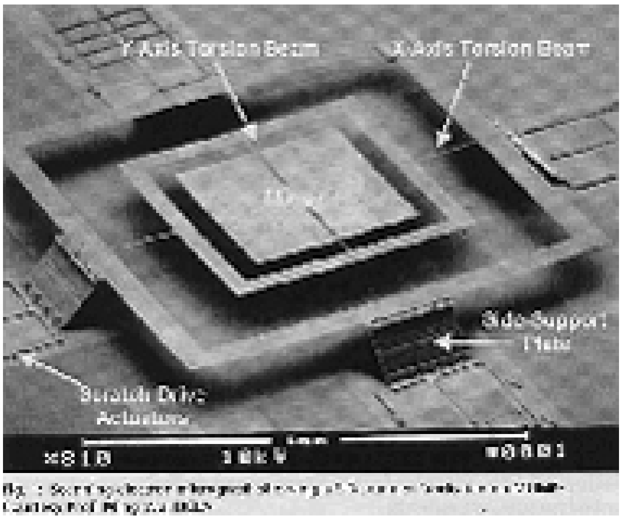
Micromachining methods

There are two main technologies for micro-manufacturing:

- Bulk micromachining



- Surface micromachining



With the following characteristics:

Bulk		**Surface**
~ 5 µm	Size of the object	< 1 µm
~ 1 µm	Particular size	~ 1 µm
~ 100 µm	Thickness	~ 1 à 3 µm
Digging of holes, trenches, lines		Deposit of thin layers

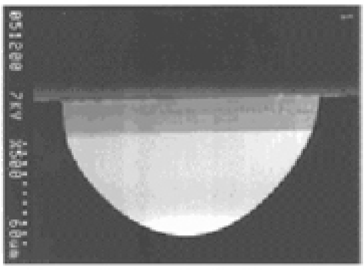
5.1. Bulk micromachining

Bulk micromachining is about putting an object, of which parts have been protected by a mask, through a chemical attack in plasma phase, vapor phase or liquid phase.

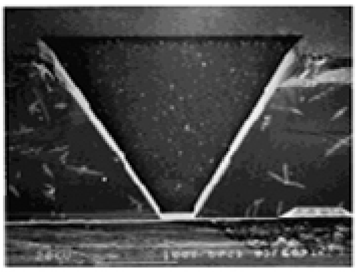
A lot of information is available today about etching speeds under different conditions, which makes it possible to control the geometry of the etched object.

According to the etching method chosen, it is possible to obtain:

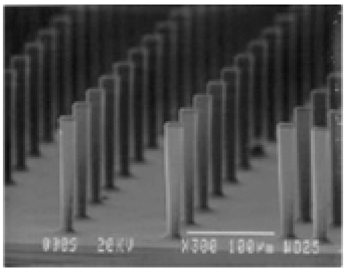
- an isotropic etching, for which the etching happens in an (almost) equivalent way in all directions from the attack point OR,
- an anisotropic etching, in which the etching happens in precisely defined directions.



isotropic



anisotropic



anisotropic

Isotropic etching usually leads to an underetching phenomenon overflowing under the masked parts.

On the contrary, with anisotropic etching it is easier to control the geometrical parameters, but the process is more difficult to implement.

Two particular technologies are used:

- Wet etching methods that use a chemical reaction: their characteristics are a low resolution, a difficulty to direct the etching direction and a limitation to 2D geometry. In most cases, the etching is stopped by rinsing or reaching a barrier layer;
- Dry etching methods that use a physical etching process (ion or electron beams bombardment, etc.). Their characteristics are a high definition, an easily directed etching direction and unlimited 2D geometries.

Exemple : Isotropic wet etching of silicon and glass

The solutions used are acid solutions (HNA, mix of HF, HNO_3 and CH_3COOH for Silicon or HF-only for Silica).

Temperature: $25°C$

Speed: 1 to $20\mu m/mn$

Stopped by nitrure or, if necessary, SiO_2 for Silicon.

Exemple : Anisotropic wet etching of silicon

Contrary to isotropic etching that use acid solutions, anisotropic wet etching can be done using highly concentrated alkaline solutions (highly basic solutions) of KOH (potassium hydroxide), EDP, TMAH etc.

The etching is slow depending on the planes: $13\mu m$ for (111), 60 times quicker for the (100) and (110) planes.

Temperature: $> 50°C$

However, this etching process isn't totally manageable yet!

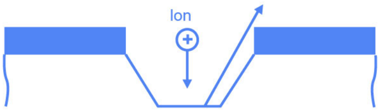
Exemple : Dry etching of Silicon and glass

It is the attack of a substrate by the ionic species contained in gas or plasma.

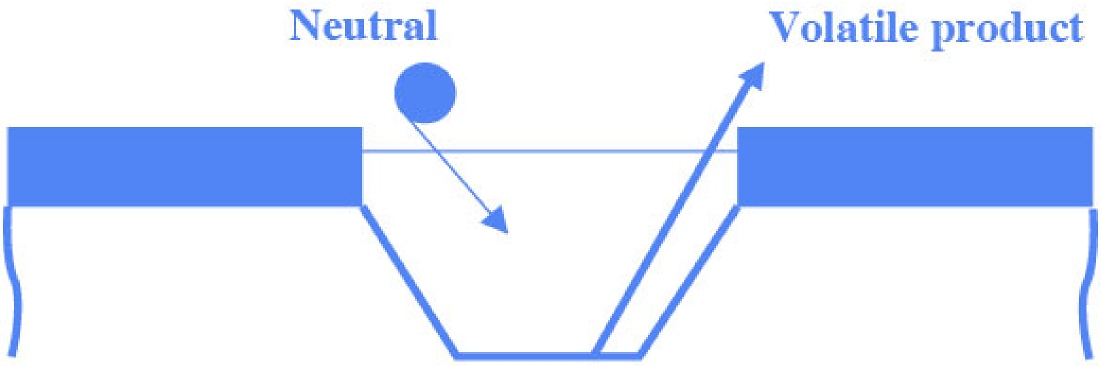
This type of etching is very rich: the form obtained can be isotropic or anisotropic depending on the conditions of etching. The anisotropic characteristics is controlled by the system and not the crystallographic orientation of the object etched (it is thus possible to etch straight channels on glass).

By playing on the nature of the plasma that contains the ions, four types of etching are possible:

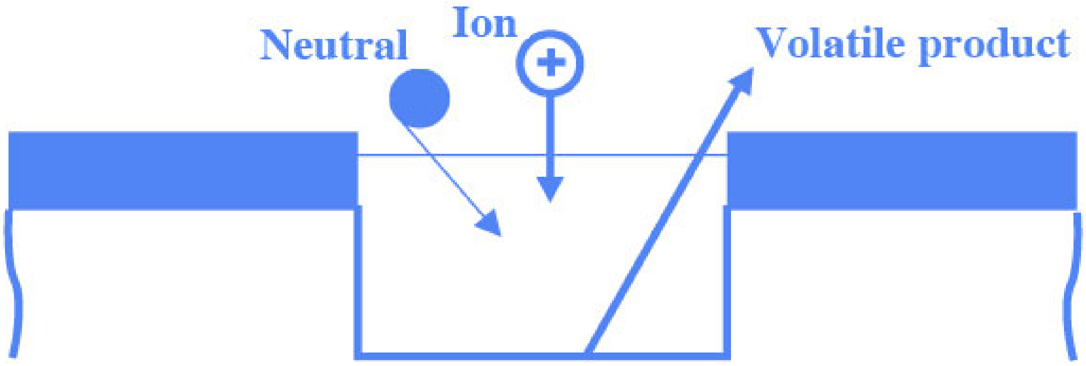
- Physical etching (sputtering): ions are accelerated, using an electric field, towards the surface of the object (target) and this leads to an anisotropic etching that is not really selective. The sputtering is usually done at a low pressure in order to avoid redeposit of matter. The etching speed of Silicon is between 0.6 and $18\mu m$ per minute.



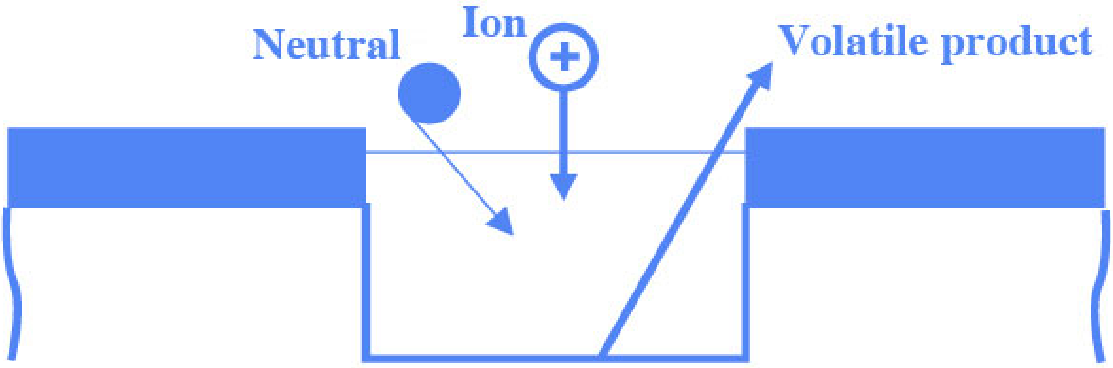
- Chemical etching: the object to etch is in contact with reagents contained in the gas or plasma that travels to the surface of the target under the effect of an electric field. Chemical reactions thus happen on the surface, producing volatile species and holes. Silicon etching is anisotropic, and its speed is of a few µm per minute. The etched surface is rough.



- Physical chemistry etching: the two former actions are combined. This type of etching is known as Reactive Ion Etching (RIE✯), and is the process used most often in micro-manufacturing. The etching is anisotropic with an etching speed for Silicon of $0.1\mu m$ per minute. It is often used to etch Silica glass.

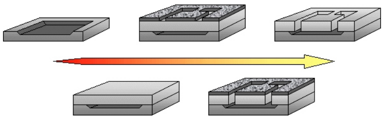


- Physical chemistry etching with an inhibitor: this is a sophisticated process that requires depositing protective layers on the sides of the etched cavities, while the bottom is chemically and physically attacked. This type of process allows for deep anisotropic etchings ($> 500\mu m$) with a high aspect ratio (30:1), hence its name: Deep-RIE. The etching speed is between 2.5 and $4\mu m$ per minute.

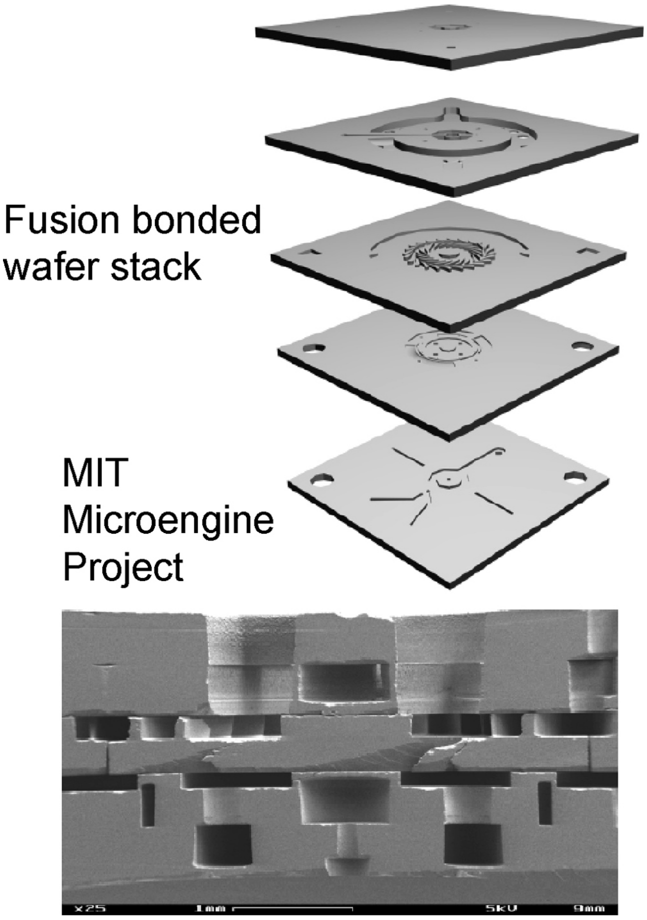


Exemple : Fusion Bonding, Silicon On Insulator or Wafer welding processes

The process requires etching a large pattern (a rectangle, for example) on the surface of the substrate wafer. A second wafer is welded by fusion to create a cavity. The final pattern (single-fit beam, suspended plate, etc.) is made on the top wafer using Deep-RIE.



It is thus possible to create complicated forms by piling up various wafers (Si-Si or Si-glass).



M. Schmidt, 2000

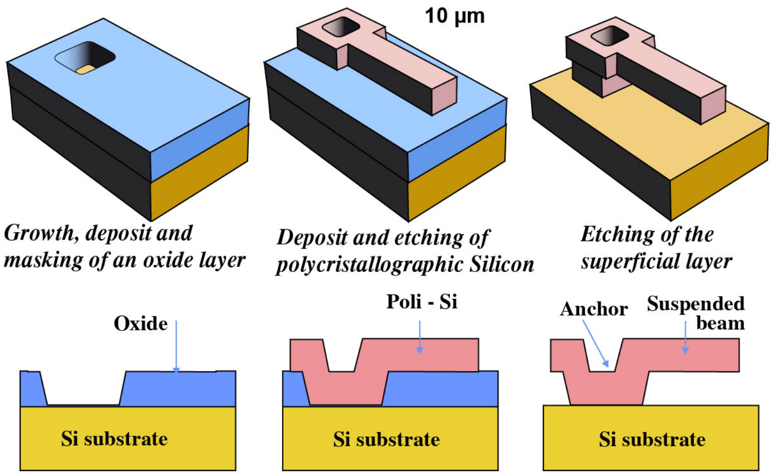
Exemple : Micromachining processes including LIGA process

Those sophisticated technologies allow for good form factors, but they are complicated to implement and expensive, especially because they often requires an X-ray lithography or a Synchrotron lithography.

5.2. Surface micromachining

It's a layer-on-layer machining technique.

Several layers are deposited on a substrate using thin films deposition processes (Chemical Vapor Deposition - CVD✭, sputtering, etc.) and some of these layers are then taken off (sacrificial layers) in order to free mobile structures (like swiveling micro-mirrors).



Growth, deposit and masking of an oxide layer

Deposit and etching of polycristallographic Silicon

Etching of the superficial layer

Those structures are sometimes elevated vertically in order to create optical surfaces perpendicular to the substrate.

The deposit is an operation that plays an important role in all micro-manufacturing processes. At present, there are a lot of different techniques that allow the deposition of all kind of materials: insulators, metals, semiconductors, polymers, proteins, etc.

A good part of the deposition techniques can be divided in two categories:

- **Physical Vapor Deposition (PVD✯),** where the object-target is put in contact with a gas that contains chemical species that absorb on the surface and form a thin film.
- **Chemical Vapor Deposition (CVD✯),** where the chemical species in contact with the target react on the surface and form compounds that are chemically linked to the object.

In the latter case, there are two possibilities:

- the reaction takes place in the gas and the products of this reaction are absorbed on the surface of the target. The reaction is said to be homogenous,
- the reaction takes place on the surface of the target. The reaction is said to be heterogeneous.

Most of the CVD✯ deposition machines are based on heterogeneous reactions, and it is easy to understand that the layers produced adheres better than with a homogenous reaction.

The CVD✯ method makes it possible to deposit insulators (for masking or electrical insulation) and polycristallographic Silicon (for surface micromachining).

The deposit speed is always slow (around $1\mu m$ per hour), which is a problem for creating thick microstructures and most of the structures reproduced are only a few microns highs.

Exemple : Examples of Physical Vapored Deposition

Thermal evaporation:

The material to deposit is placed in a crucible facing the target and brought to high temperature, thus evaporating (or sublimating). Evaporation produces an atom flow which adsorbs to the target's surface.

Other molecules contained in the chamber are also deposited. Therefore, it is necessary to work at a low pressure to avoid any unwanted deposit or contamination.

The thermal deposit method is often used in laboratories because of its simplicity.

Sputtering:

This method is often preferred to thermal evaporation because it allows a greater range of materials to be deposited and a better adhesion of the various coatings.

A cold plasma has to be created and the method is similar to the one used for physical dry etching. However, for sputtering, the target has to be placed on the anode. The crucible containing the material or sample to sputter is placed on the cathode.

Energized ions are collected on the target and penetrate one or two of the molecular coatings of the substrate, thus leading to better adhesion.

Exemple : Examples of Chemical Vapored Deposition

LPCVD✭: Low Pressure Chemical Vapor Deposition

With this method, the deposition occurs at a low pressure.

The target is heated to a high temperature (several hundred degrees Celsius) and thermal activation allows heterogeneous chemical reactions.

This method is used in polycrystalline silicon deposition.

APCVD✭: Atmospheric Pressure Chemical Vapor Deposition

In that case, deposition occurs at atmospheric pressure.

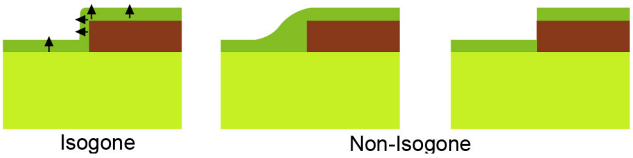
PECVD✭: Plasma Enhanced Chemical Vapor Deposition

When thermal activation is not sufficient to allow chemical reactions, a plasma is used to activate those reactions on the target's surface, by accelerating ions towards the surface.

Remarque

The evaporation of a material on pre-existing relief does not necessarily produce a uniform coating. Two cases stand out:

- conformal deposition: In this case, the coating's thickness is constant on the whole surface of the target. Therefore, it adapts to the relief on the surface of the target;
- non-conformal deposition: The coating's thickness is not uniform. Lumps and pits form where the relief differs.



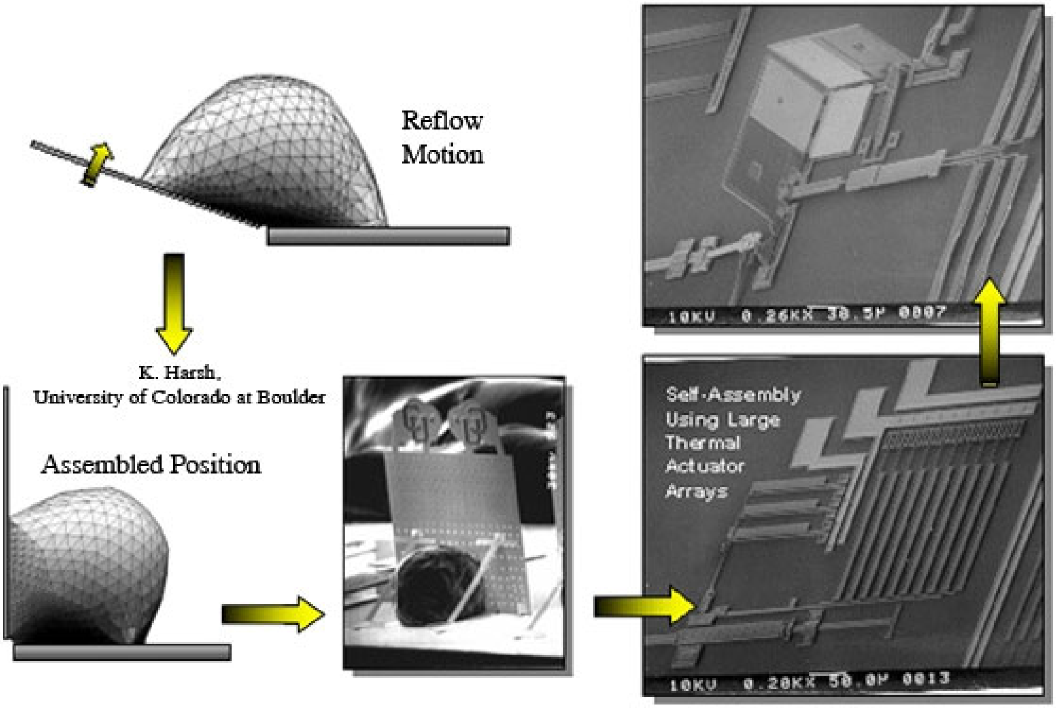
Remarque : Specific case: silicon layers manufacturing

Given that silicon reacts with oxygen from the air at high temperatures, it is possible to obtain up to a $2\mu m$ layer of silicon oxide on the surface of a pure silicon wafer (3 hours at $1000^\circ C$).

5.3. Automated assembly of MOEMS

Surface micromachining techniques can only be used for manufacturing 2D structures.

An alternative consists in the use of rotating figures to create complex 3D structures. An assembly of two elements welded by a common edge is used. The minimization of surface energy during the contraction of the cooling weld makes one of the elements fall in its final position by rotating around the axis of the welding.

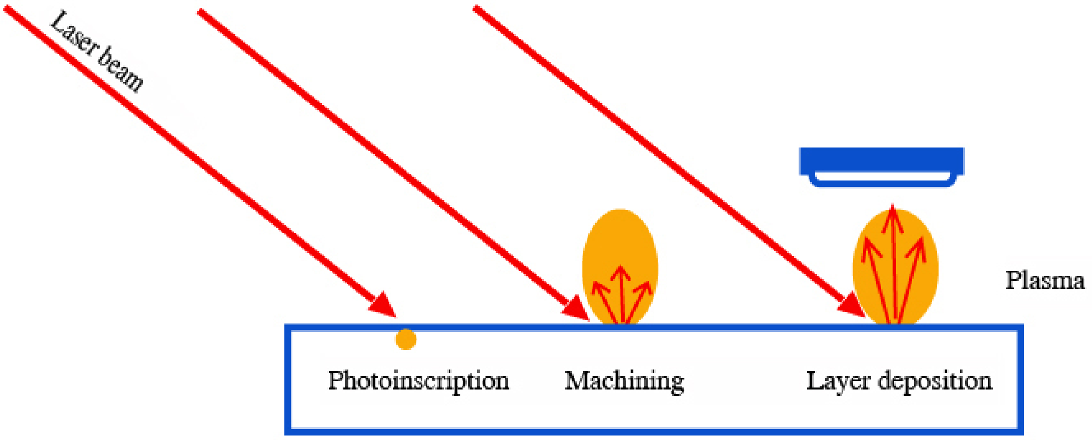


Advantages of this method:

- allows sub-micronic precision for the parallel assembly of many elements;
- allows assembly control with guides for translation or rotation;
- eliminates the need for external macrostructures;
- allows the creation of mechanical, electrical or thermal contacts and interconnections;
- is reliable.

5.4. Another micromachining process: laser ablation

This recent machining technology uses an intense ultrashort-pulse (femtoseconds) UV or IR laser beam.



Summary of processes using ultrashort pulses

The advantage of ultrashort-pulse beams is the absence of collateral damage.

Advantages of fs pulses:

- A high-intensity electric field,
- Electrons are pulled apart of external layers,
- Positive ions are created and repel each other,
- Ejected material is assumed to be athermal.

Almost all materials (from steel to polymeric materials) can be pierced using this technique but resolutions remain low, only a few dozen μm.

6. Characterization of microsystems by optical measure

Techniques based on optical interferometry offer precious data on microdevices designed to activate, be activated or distorted.

Furthermore, those measures do not require contact.

They can be used to measure:

- A component's 3D profile,
- Deflection parameters of a microactuator,
- Dynamic 3D distortion profile of a micromirror,
- Thermal behavior of a microcomponent when heated,
- Detection of manufacturing defects or strains,
- ...

7. Interaction between light and microstructures

Case of a molecule

- Light scattering is created by harmonic oscillation of the induced dipole.

Case of nanoparticles

- For an insulating material, it is Rayleigh scattering (as for the sky blue);
- For a semiconductor, a resonance absorption occurs when the energy level exceeds the band gap energy, alongside with a fluorescence phenomenon depending on the nanoparticle's size,
- For a metal, a resonance absorption occurs matching the surface plasmon's frequency, without light emission.

Case of microparticles

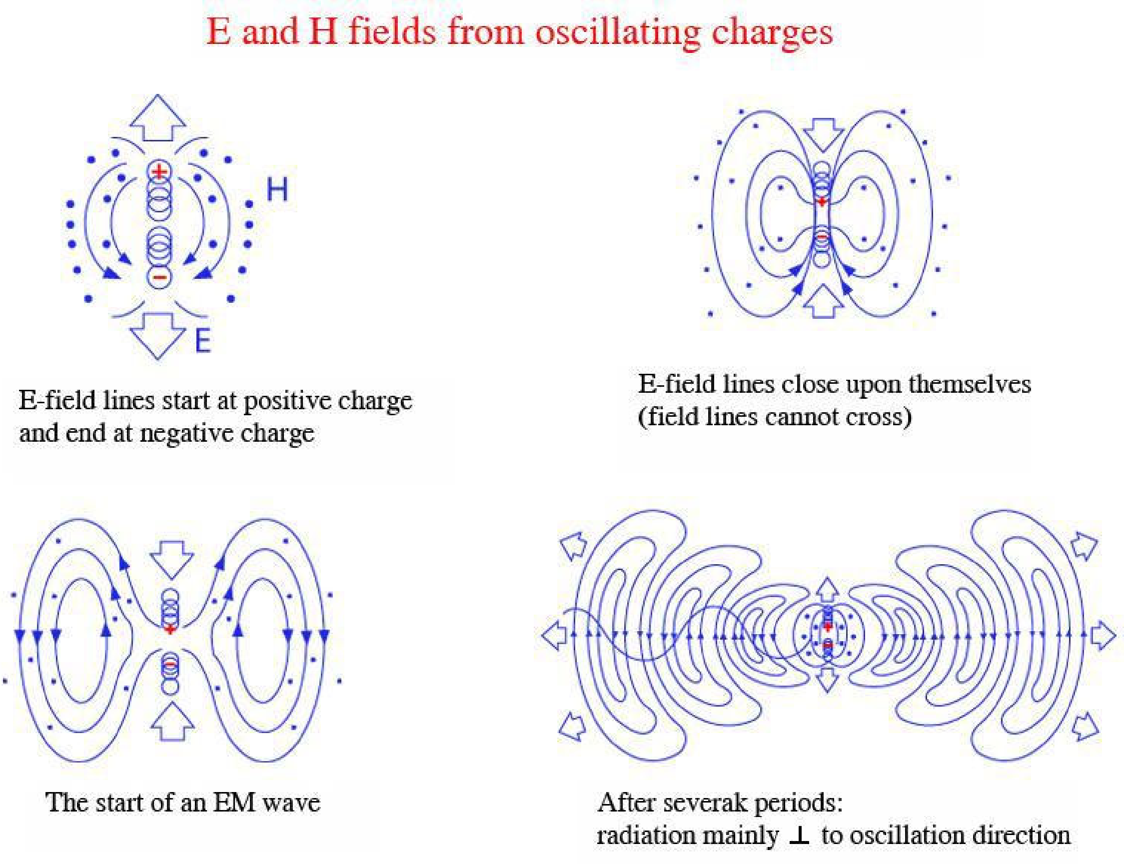
- For particles of size equal or superior to an optical wavelength, forward scatter increases and a rainbow appears because of water scattering.

Light scattering by insulating molecules or nanoparticles

An insulating molecule or nanoparticle becomes polarized in the presence of an electromagnetic field. The oscillating electric field of the incident wave provokes a harmonic oscillation of the electrons and the nucleus around a balanced position. This position can be described using atomic polarizability and the Lorentz model:

$$p = \frac{e^2}{m} \cdot \frac{1}{(\omega_o^2 - \omega^2 - i\gamma\omega)} \cdot E_L$$

With the electric field lines starting with a positive charge, ending on the negative charge and not crossing, the emission of electromagnetic radiation is observed after several oscillatory periods of the charges along the axis of the dipole formed by the electron and the nucleus. This radiation is oriented at the perpendicular of the oscillation movement and depends on the θ angle with this perpendicular.



E and H fields from oscillating charges

E-field lines start at positive charge and end at negative charge

E-field lines close upon themselves (field lines cannot cross)

The start of an EM wave

After severak periods: radiation mainly ⊥ to oscillation direction

The radiated intensity of a dipole "p" can be computed with the following equation:

$$I = \frac{p^2\omega^4}{32\pi^2 \in_o c^3 r^2} \sin^2\theta$$

and the total emitted power with:

$$P_s = \iint_A I \cdot dA' = \frac{p_o^2\omega^4}{12\pi\omega_o c^3}$$

In which A is a closed surface surrounding the dipole.

Consequently, the emitted intensity of a Lorentz dipole subjected to an external electric field E_L is:

$$I = \frac{e^4\omega^4}{32\pi^2 m^2 \in_o c^3 r^2}\left(\frac{1}{\omega_o^2 - \omega^2 - i\gamma\omega}\right)^2 E_L^2 \sin^2\theta$$

Leading to the conclusion that:

- Scattering is stronger near a resonance frequency,
- Scattering is stronger for higher frequencies or lower wavelengths,
- Scattering occurs forwards and backwards at the same time.

Exemple : Case of a noiseless scattering (the sky blue color)

Oxygen (O_2) and nitrogen (N_2) molecules in the air have higher resonating frequencies than visible wavelengths, i.e. $\omega_o >> \omega$. Consequently, when illuminated by solar light, the scattered intensity corresponds to:

$$I_s \approx \frac{e^4 \omega^4}{32\pi^2 m^2 \in_o c^3 r^2} \frac{1}{\omega_o^4} E_L^2 \sin^2 \theta$$

Therefore, for a wavelength twice as short, scattered intensity is $2^4 = 16$ tmes stronger and thus the highest wavelengths in the solar light spectrum (i.e. near red) are the least scattered and shorter wavelengths (near blue) are 16 times more scattered.

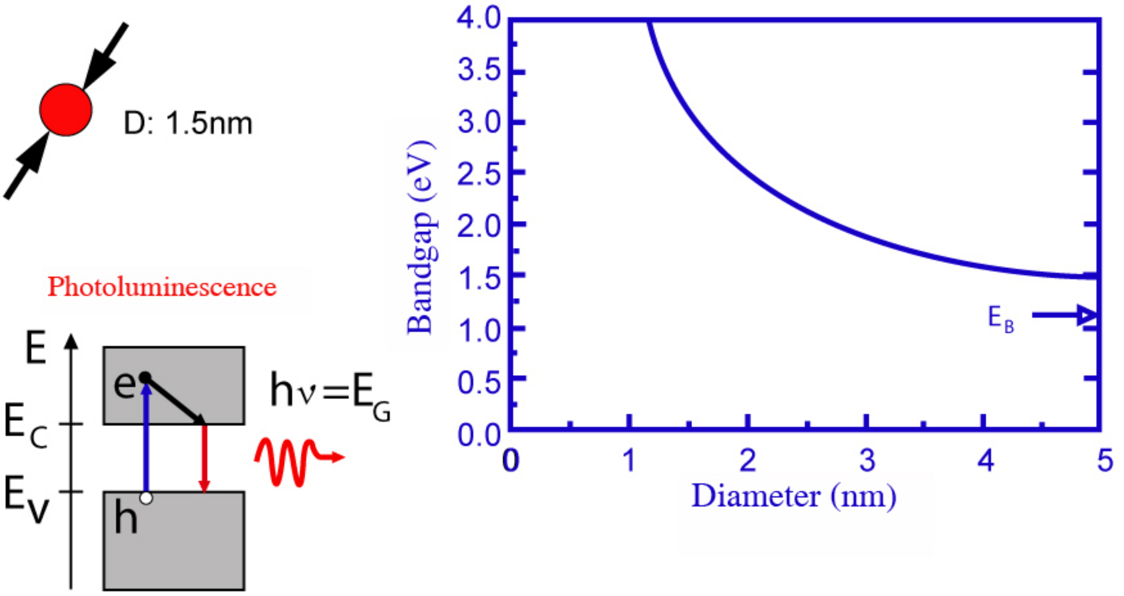
The same thing happens when nanoparticles are illuminated.

Light scattering by semi-conducting nanoparticles

When a semi-conducting material is illuminated by a luminous energy radiation exceeding the band gap energy, electrons from the valence band can jump to the conduction band by creating a hole. Thermal equilibrium is restored when the electron-hole couple is recombined and a radiation corresponding to the band gap energy is emitted. Photoluminescence occurs if band gap energy corresponds to an optical radiation.

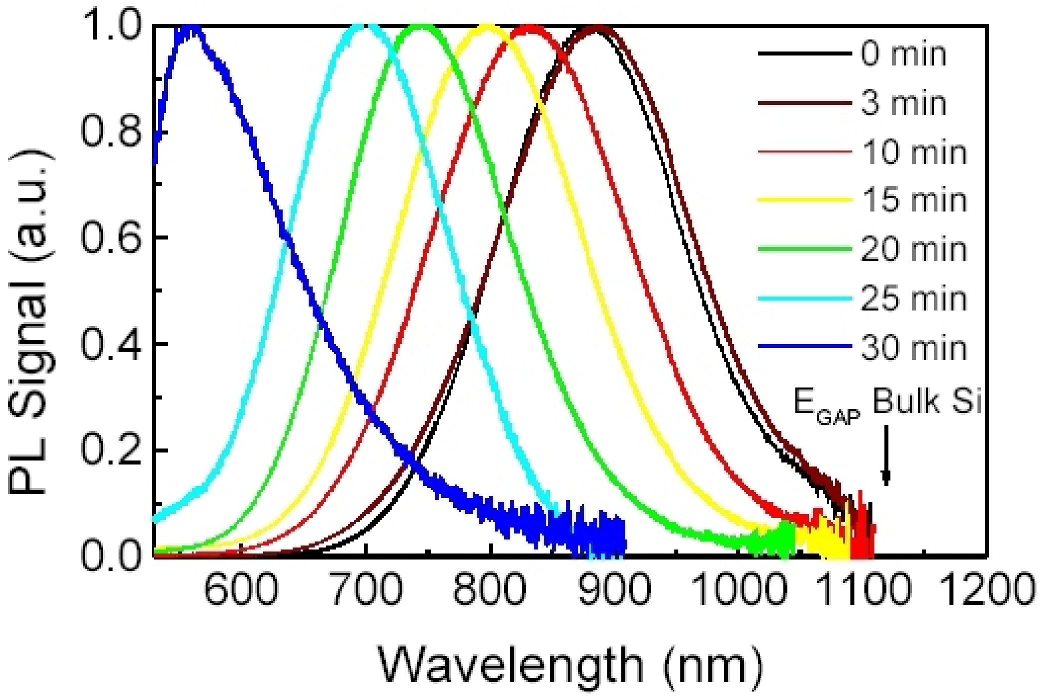
For silicon (Si✭) nanoparticles, band gap energy depends on the nanoparticle's diameter (C. Delerue and al. [Theoretical aspects of the luminescence of porous silicon] Phys. Rev. B48, 11024, 1993).

Influence of the diameter on the Si nanocrystals' luminescence



With a diameter less than $5nm$, those nanoparticles can be embedded by sending a $50keV$ monoatomic silicon beam on a $100nm$ SiO_2 silicon plate. The size of nanoparticles can be modified by provoking oxidation thanks to the oxygen contained in silicon, by increasing the temperature to reach about $1000°C$.

When illuminating the nanoparticles with a $458nm$ wavelength purple radiation ($P = 10mW/mm^2$, $T = 293K$), a radiation with a wavelength below that of pure solid silicon's band gap energy is observed. The longer the oxidation time (and thus the smaller the nanoparticles), the weaker the radiation.



This example shows that the optical properties of small semi-conducting objects are strongly influenced by their nature and size. Thus, three categories can be drawn depending on the average emission wavelength (M. Bruchez and al [Semiconductor Nanocrystals as Fluorescent Biological Labels] (Alivisatos group), Science, 2013, 281):

- *Red series* : InAs nanocrystals -3 to $6nm$ diameter;
- *Green series* : InP nanocrystals -3 to $5nm$ diameter;
- *Blue series* : CdSe nanocrystals -2 to 5 nm diameter;

This could be exploited in the making of biochips by marking biomaterials with semi-conducting nanocrystals emitting visible light.

Light scattering by particles or objects the same size as the wavelength

Starting again from the theory giving the scattered intensity of a dipole which size is much smaller than the wavelength, if the dipole's size approaches the wavelength, forward scatter increases.

If the dipole's size equals twice the wavelength, forward scattering is particularly strong, but other things can be observed:

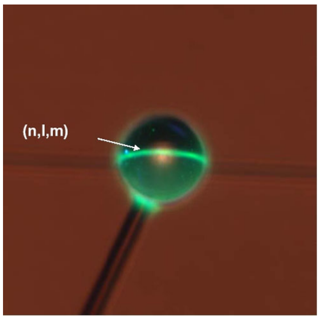
- maximums of diffusion in different directions for some wavelengths whose repartition is centered around the incident direction (producing the “rainbow” effect observed with water droplets),
- the same light intensity repartitions for some groups of wavelengths, resulting in “white clouds”.

Exemple : Case of microspheres with a diameter of d >> λ

Silica microspheres with a diameter of $100\mu m$ can be created by heating the tip of a hollow silica rod that has previously been collapsed.

Now, if we take a tapered optical fiber with a core diameter of only a few micrometers and place it close to the microsphere perpendicularly to one of its diameters, coupling of the light transmitting through the fiber to a gallery mode propagating along a circle on the microsphere's surface can be observed (Ming Cai, Oskar Painter and Kerry Vahala [Observation of Critical Coupling in a Fiber Taper to a Silica-Microsphere Whispering-Gallery Mode System], Phys Rev Lett 85, 74, 2000).

If the silica microsphere has been implanted with Erbium (Er), it lases!



The microsphere then acts as a microresonator whose performance can be characterized by the quality factor Q:

$$Q = \frac{\text{Lifetime of a photon}}{\text{Optical period}}$$

For a "conventional" laser resonator, a quality factor Q around $10^3–10^4$ is considered excellent. The quality factor Q of a resonator composed of a $100 \mu m$ silica microsphere has been measured near 10^{10} by M.L. Gorodetsky, A.A. Savchenkov and V.S. Ilchenko [ULTIMATE Q OF OPTICAL MICROSPHERE RESONATORS] (Opt. Lett. 21, 453, 1996) !!!

Thus, microspheres open diverse perspectives of application such as:

- Low threshold microlasers,
- Narrow-band optical filters,
- Highly sensitive sensors with various layers,
- Multiplexers for telecommunications,
- Non-linear optics,
- Quantum electrodynamics experiments,
- ...

8. Bibliography

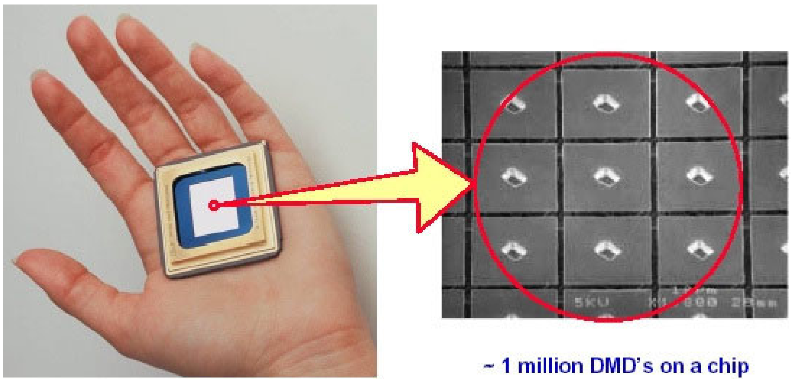
For further information, please consult the following works:

- Monograph [[Fundamentals of Microfabrication]]
- Articles [[MEMS : fabrication, design and applications], [Les microsystèmes], [MEMS for optical functionality], [A MEMS based projection system], [III-V semiconductors based MOEMS devices for optical telecommunications], [Micromachinery, rolling at last ?], [Active opto-electronic components], [Silicon as a mechanical material], [Optical MEMS for Lightwave Communications], [Introduction to the issue on Optical Mirco and Nana systems]]
- Internet resources [,,,,,,,, [Venus tout droit du pays des lilliputiens, les MOEMS vont envahir l'espace], [Understanding optical communications],,]
- Conferences [[Introduction to MEMS], [A design flow for MEMS], [Short course on Optical-MEMS]]
- Thesis [[Optical Propagation methods for system-level modeling of optical MEMS]]

III.Case study: adjustable micromirrors

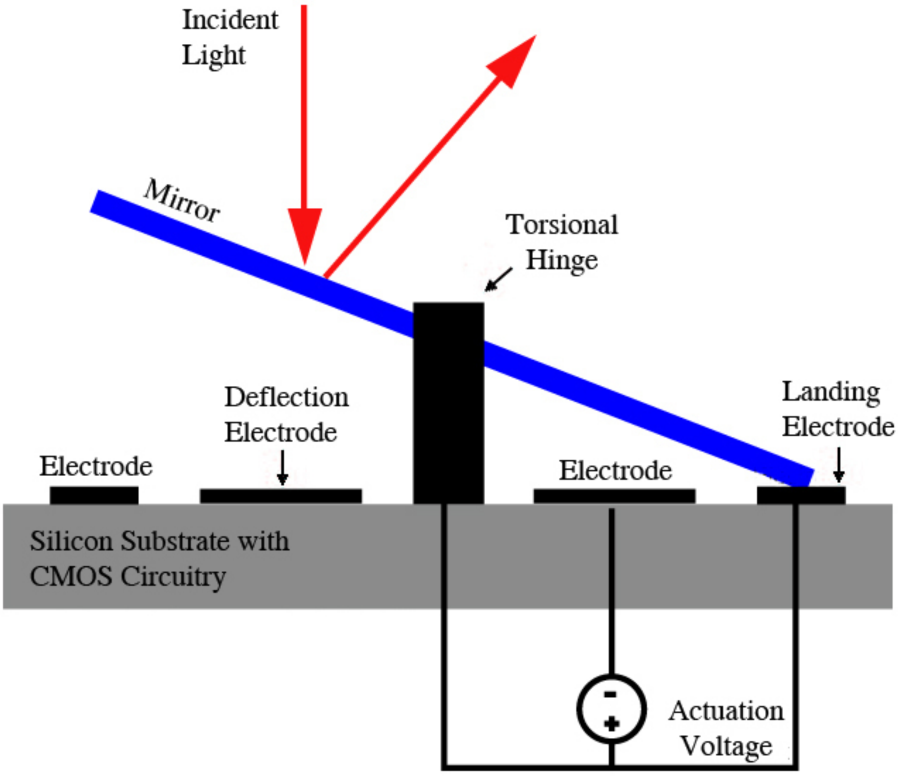
Adjustable micromirror systems are probably the most complex existing light valve systems. This case study is based on the properties of adjustable micromirrors manufactured by Texas Instruments for projection systems. These systems use adjustable micromirrors based on the DMD (*Digital Micromirror Devices*) technology. This study only deals with the micro-optic aspect of those objects. Addressing and signal processing will not be examined.

The adjustable micromirror systems studied here consist of a rectangular array of hundreds of thousands of adjustable microscopic mirrors. The size of each mirror is inferior to a fifth of a hair's width and corresponds to a pixel in a projected image.

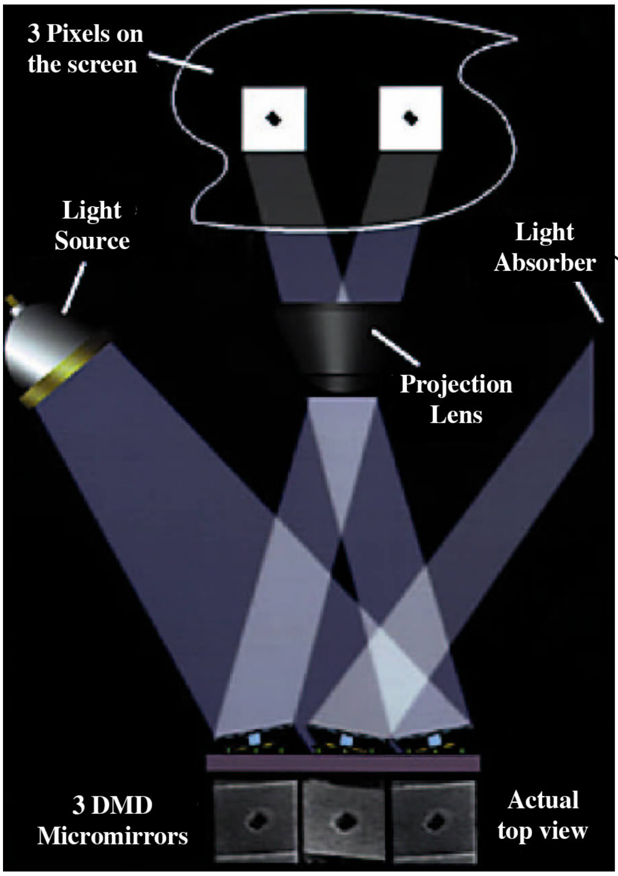


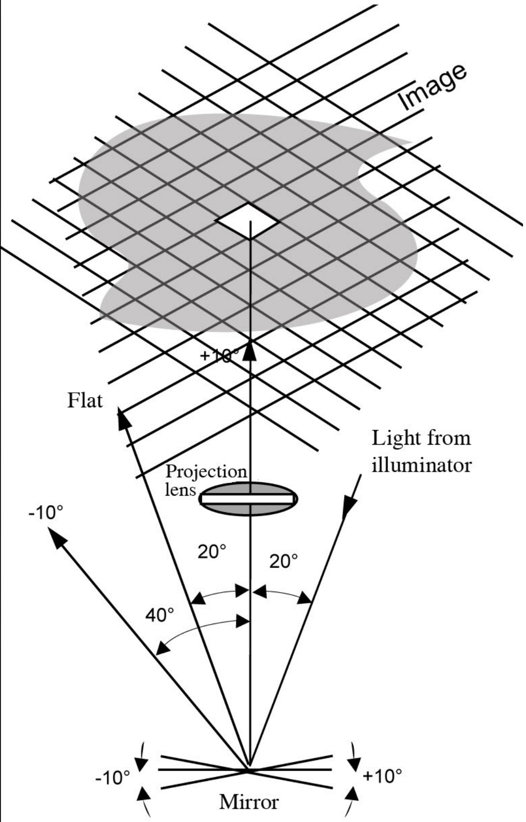
~ 1 million DMD's on a chip

The structure of each mirror is described in the following diagram:



alongside with the projection system's mechanism:



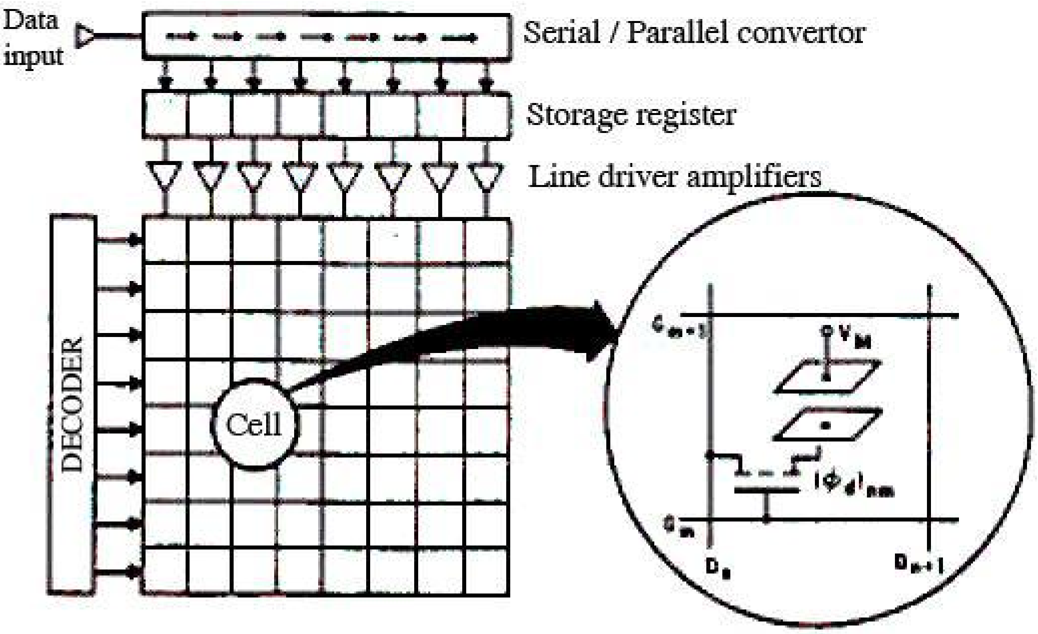


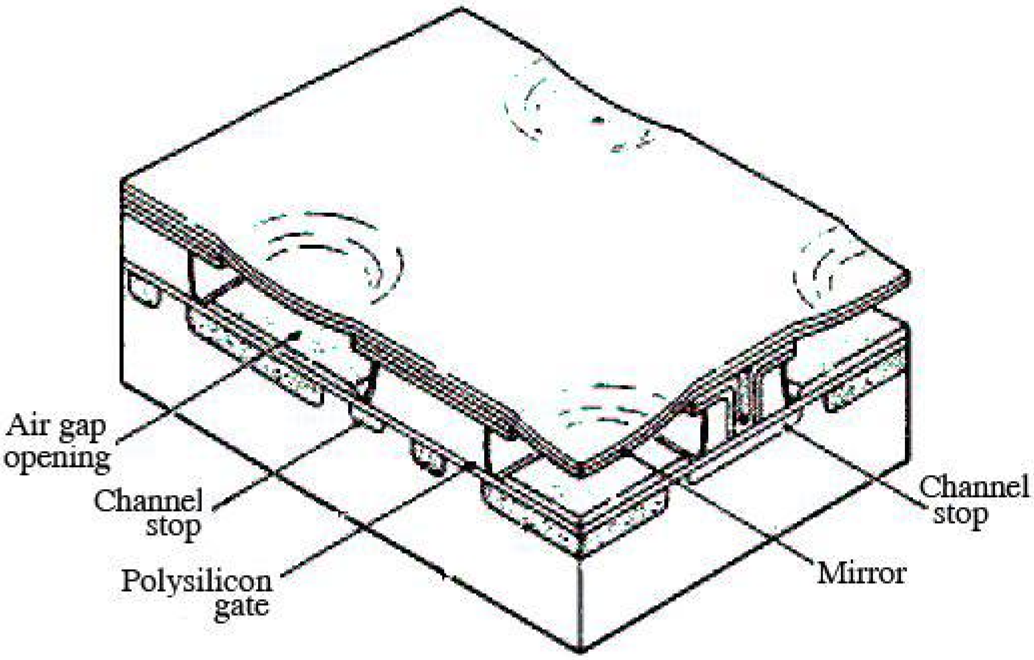
Those projection systems are characterized by:

- High luminance,
- High contrast,
- Digitally controlled grey-scales,
- Reduced size and weight,
- Low energy consumption,
- Usefulness in portable systems.

1. Origins and development

Before DMD✯ (*Digital Micromirror Devices*), there were DMDs as in “*Deformable Mirror Devices*”:





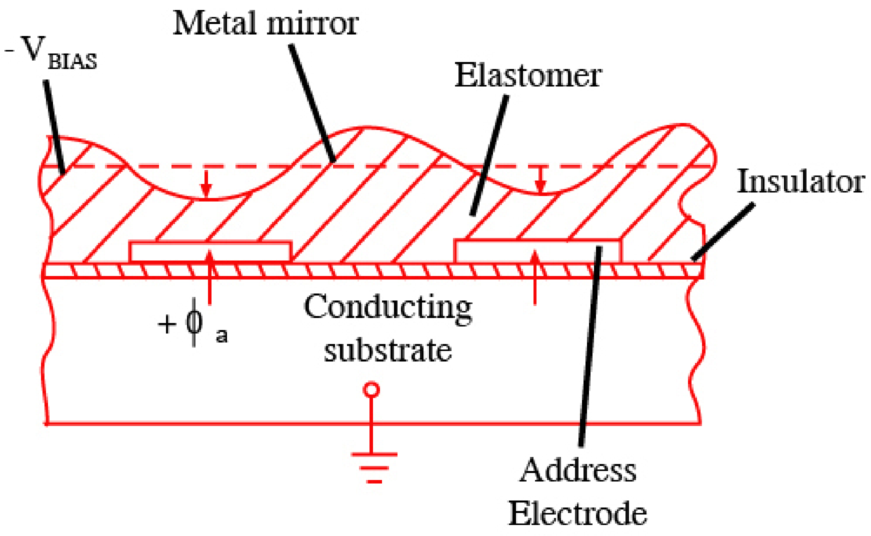
Perspective view of DMD

The first of this type was created in 1980, using localized deformation on a metallic mirror (SLM✯ : *Spatial Light Modulator*) addressed by a 128×128 CMOS transistors matrix in a DRAM-type arrangement.

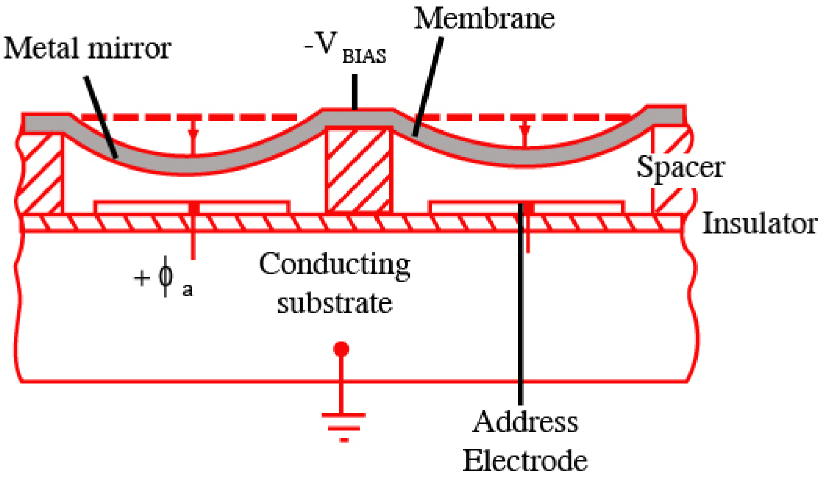
The response time of the mirrors was around $25\mu s$ with a source waiting time of $200ms$. Each pixel was $51\mu m \times 51\mu m$ and was separated from the source by a $620nm$ air gap. The active surface of the mirror corresponded to 32% of the total surface.

There were four main types of devices:

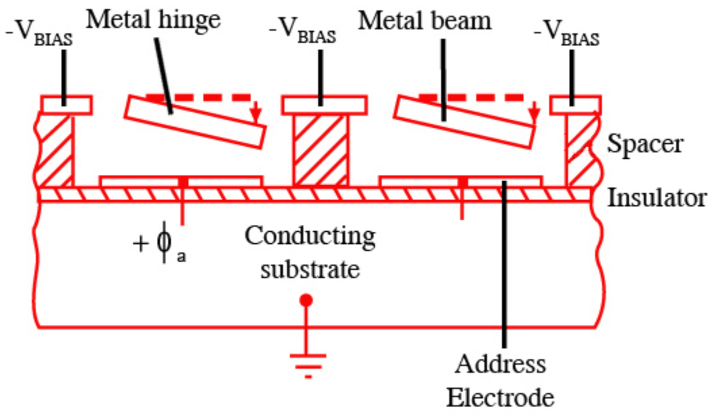
- Elastomer SLM✭: the metallic mirror was deposited on a layer of flexible elastomer covering the actuating transistors.



- Membrane SLM✭: the metallic mirror lies on a membrane suspended over the actuation transistors, separated from them by an air gap and supported by insulating pads.



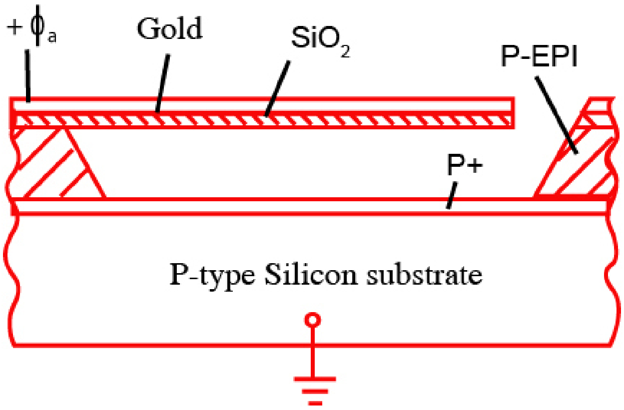
- SLM✭ with single-beam built: each metalic micro-mirror is deposited on a single embedded beam with a flexion controlled by a transistor.



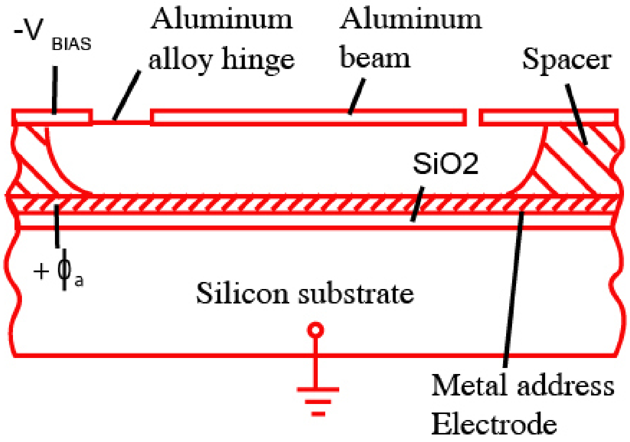
- SLM✯ with twist: each micro-mirror is deposited on a dual-embedded beam whose twist is controlled by a transistor.

For the latter two, the mirrors were created according to the devices:

- Either by depositing a gold film on silica beams micromachined by anisotropic dry etching,
- Or by depositing an aluminum film on aluminum alloy beams micromachined by plasma etching.

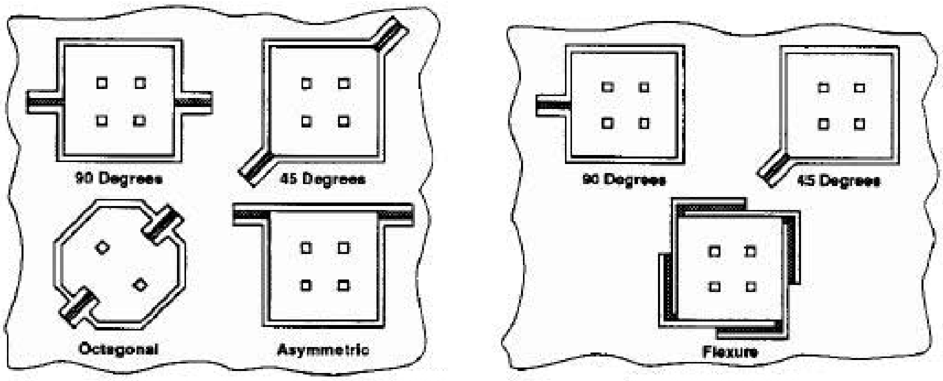


(a) Cantilever-beam formed by anisotropic wet etching



(b) Cantilever-beam formed by spun-on spacer and plasma etching

Different configurations can be compared on the following figure:

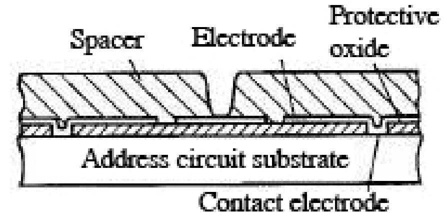


- Torsion-beam DMD
- Symetric torsion beam device has amplitude-dominant modulation

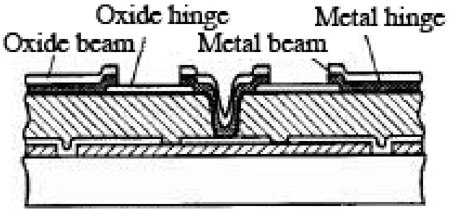
- Cantilever-beam DMD
- Balanced flexure device has phase-dominant modulation

2. Manufacturing

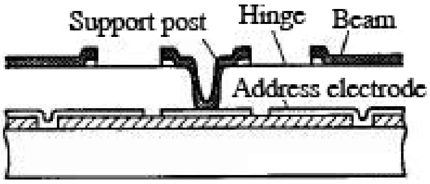
Number of mobile elements	0.5 to 1.2 million
Mechanical move	Slight contact or "bonding"
Expected lifetime	450 billion contacts for each mobile element
Addressing tension	Limited to 5 V for CMOS technology
Material for the mechanical elements	Aluminum
Manufacturing process	Low temperature, sputtering, plasma etching
Sacrifical layer	Organic layer, dry etching, wafer elimination
Separation of useless components	After elimination of the sacrifical layer
"Packaging"	Optical, hermetical, thermal isolation
Test	Quick electro-optical test before separation of useless components



(a) After spacer patterning

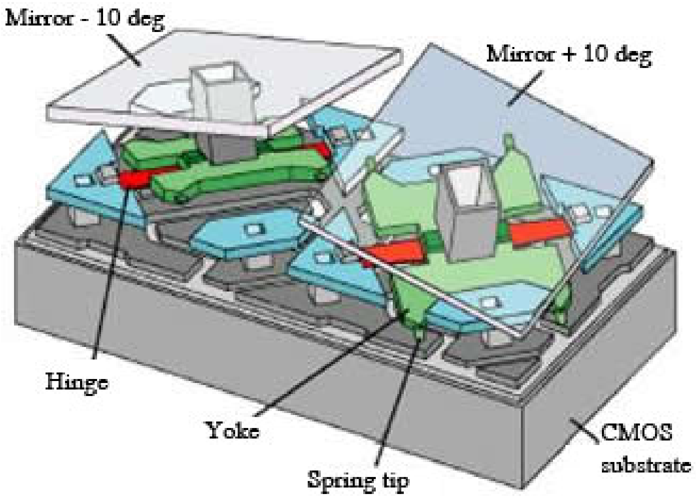


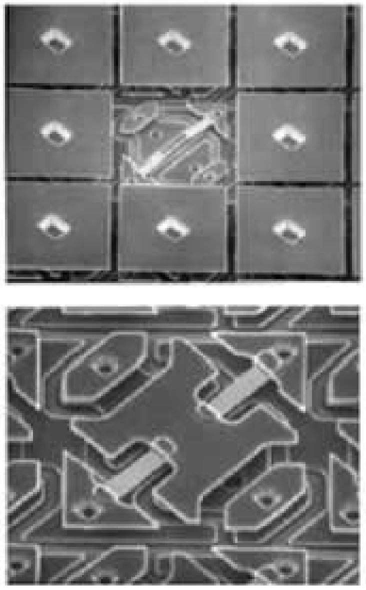
(b) After beam metal etching

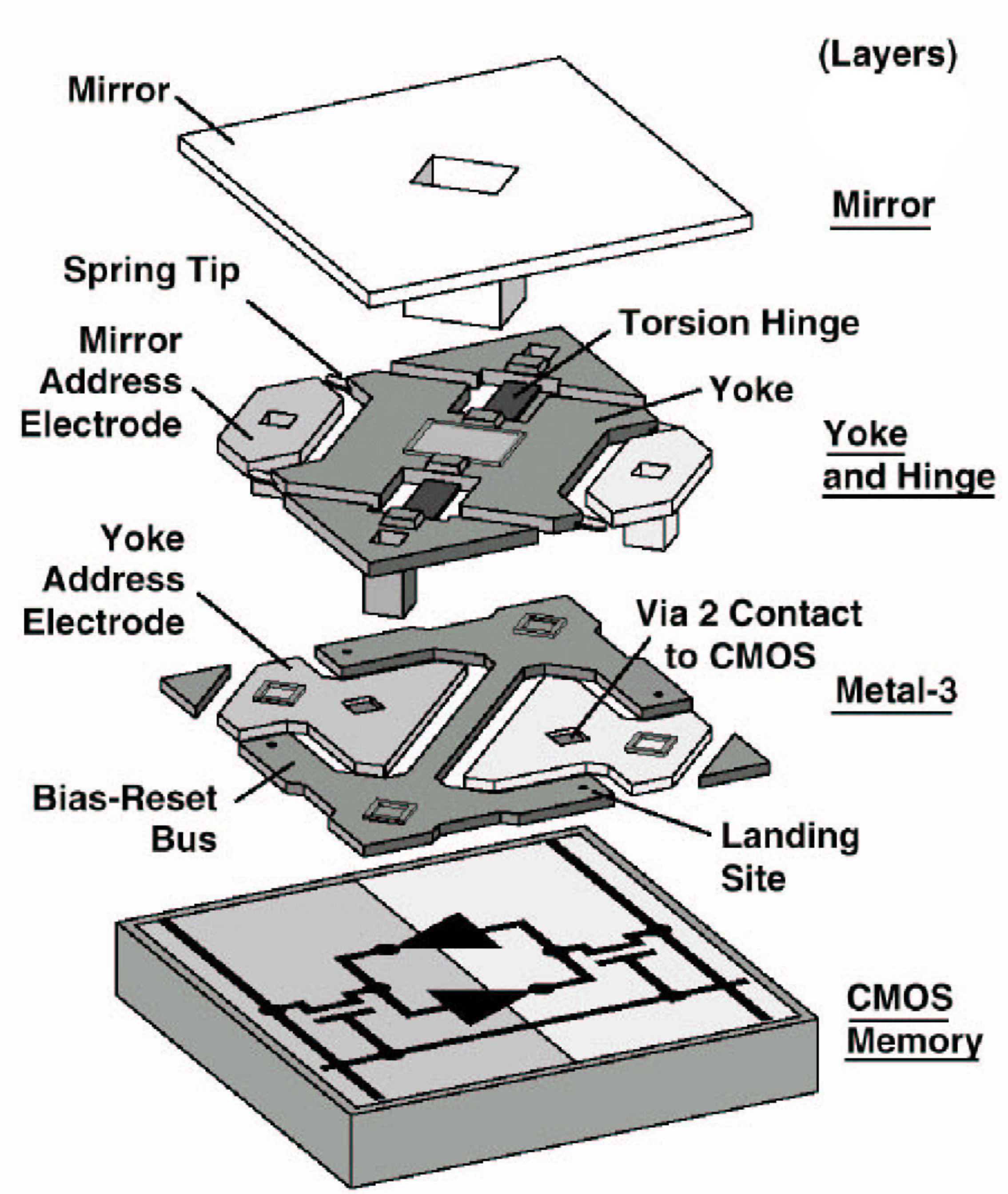


(c) Completed chip

- Aluminum alloy-based surface-micromachining process
- 2-3 µm organic sacrificial layer (it also planarize the surface)
- Hinge: aluminum alloy, typically 50 to 100 nm thick
- Mirror: aluminum alloy, typically 300 to 500 nm thick
- Dry releasing in isotropic plasma etching


Mirror - 10 deg
Mirror + 10 deg
Hinge
Yoke
Spring tip
CMOS substrate





Aluminum is used for the structure rather than polycrystalline silicon for it to be compatible with CMOS technology.

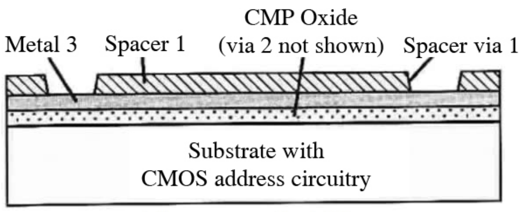
Masking of the sacrificial layer is done with a photosensitive resin hardened under UV light and the etching is done using dry plasma.

Aluminum alloys are used to improve performance:

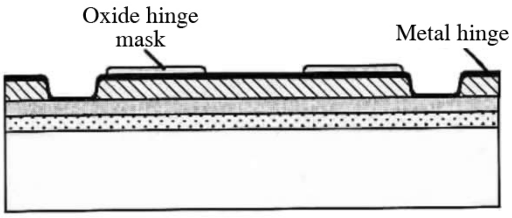
- aluminum mirrors contain a small quantity of copper and silicon,
- aluminum alloy pivots can contain up to $0,2\%$ titanium and 1% silicon.

The DMD✯'s superstructure is built on the substrate of the CMOS's memory circuit.

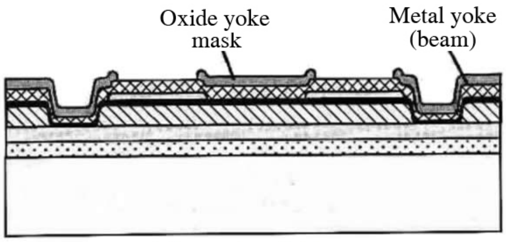
The whole structure requires 6 masking levels, as shown on the following diagram:



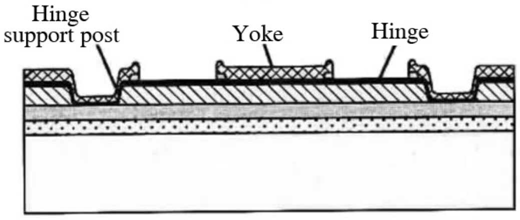
After spacer 1 etching



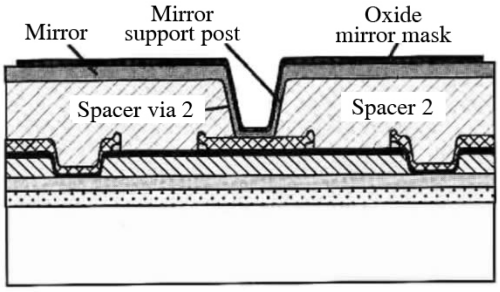
After hinge mask etching



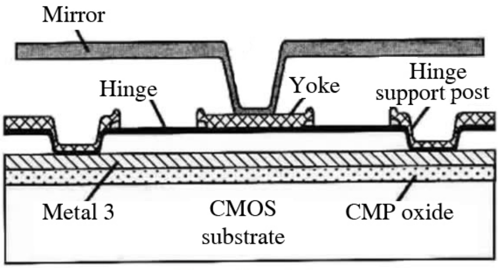
After yoke etching



After yoke/hinge etching and oxide strip



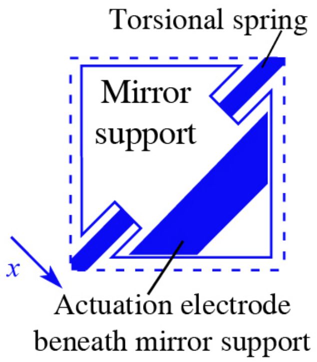
After mirror oxide etching

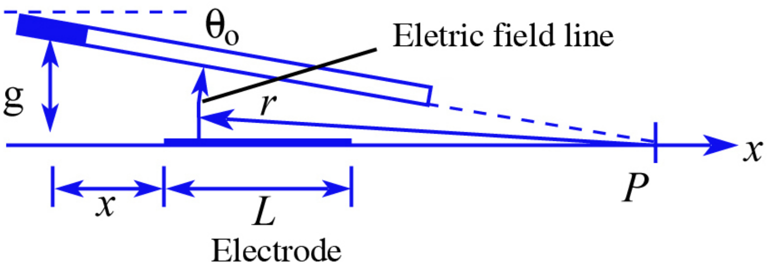


Completed device

3. Mechanism analysis

Schematic diagram for a rotating micromirror undergoing a twist (DMD✭ - *Digital Micromirror Devices* - model manufactured by Texas Instruments):





$$W(\theta_o) = \frac{1}{2}CV^2$$

$$C = \frac{Q}{V}$$

$$\Phi(\theta) = V(1 - \frac{\theta}{\theta_o})$$

$$\vec{E} = \frac{V}{r\theta_o}\hat{\theta}$$

$$Q = \int_{electrode} \in_o \vec{E} \cdot d\vec{A}$$

$$Q = \int_{electrode} \in_o \vec{E} \cdot d\vec{A} = \frac{\in_o V}{\theta_o} \int_{P-(x_1+L)}^{P-x_1} \frac{w}{r} dr = \frac{\in_o Vw}{\theta_o} \ln(\frac{P - x_1}{P - (x_1 + L)})$$

If the mirror's width w is supposed constant, then:

$$Q = \frac{\in_o Vw}{\theta_o} \ln \frac{1 - (\frac{x_1}{g}) \tan\theta_o}{1 - (\frac{x_1 + L}{g}) \tan\theta_o}$$

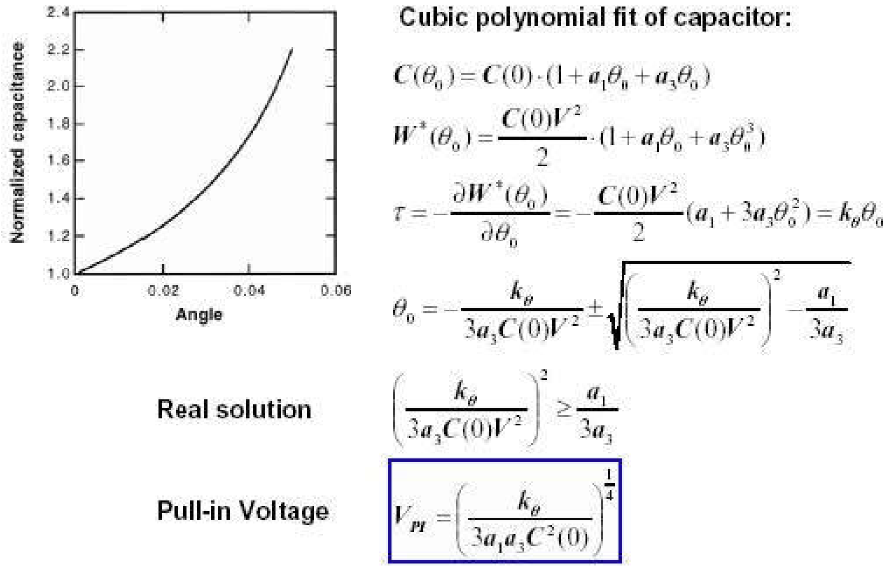
with

$$P = \frac{g}{\tan\theta_o}$$

hence the capacity:

$$C = \frac{Q}{V}$$

An approximation of the curve representing C according to the angle θ can be drawn with a polynomial of the third degree from which it is possible to deduce the rest point and the actuation tension:



Cubic polynomial fit of capacitor:

$$C(\theta_0) = C(0) \cdot (1 + a_1\theta_0 + a_3\theta_0)$$

$$W^*(\theta_0) = \frac{C(0)V^2}{2} \cdot (1 + a_1\theta_0 + a_3\theta_0^3)$$

$$\tau = -\frac{\partial W^*(\theta_0)}{\partial\theta_0} = -\frac{C(0)V^2}{2}(a_1 + 3a_3\theta_0^2) = k_\theta\theta_0$$

$$\theta_0 = -\frac{k_\theta}{3a_3C(0)V^2} \pm \sqrt{\left(\frac{k_\theta}{3a_3C(0)V^2}\right)^2 - \frac{a_1}{3a_3}}$$

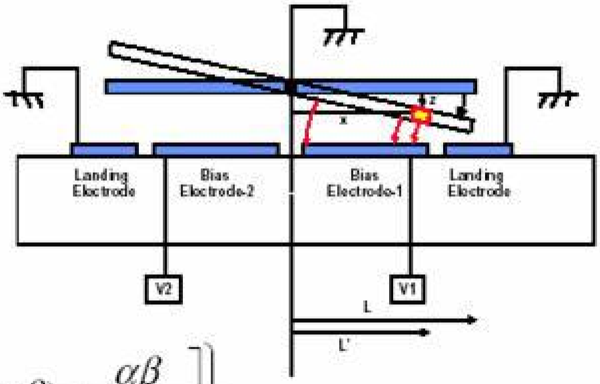
Real solution

$$\left(\frac{k_\theta}{3a_3C(0)V^2}\right)^2 \geq \frac{a_1}{3a_3}$$

Pull-in Voltage

$$\boxed{V_{PI} = \left(\frac{k_\theta}{3a_1a_3C^2(0)}\right)^{\frac{1}{4}}}$$

In the same way, a simple mechanical model can be used to obtain the other electromechanical parameters of the mirror's rotative movement:



Attractive torque

$$\tau_a = \int_0^{L'} x \cdot \frac{\varepsilon \cdot V_a^2}{2} \cdot \frac{1}{(z_0 - z)^2} dx$$

$$\tau_a = \frac{\varepsilon \cdot V_a^2}{2} \cdot \frac{W}{\tan^2 \theta_M} \left\{ \frac{1}{\alpha^2} \left[\ln(1-\alpha\beta) + \frac{\alpha\beta}{1-\alpha\beta} \right] \right\}$$

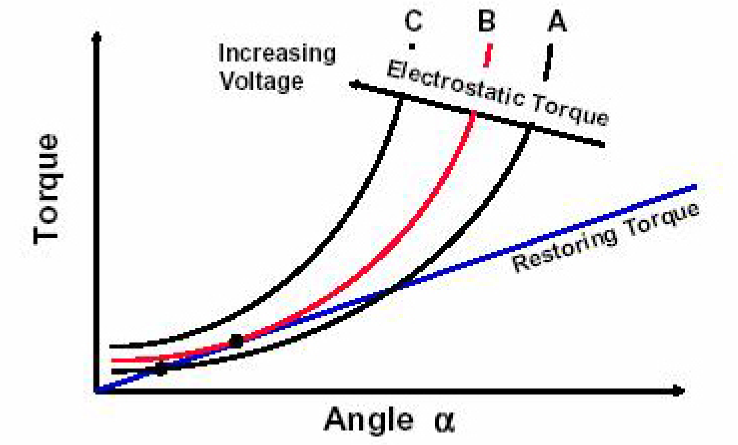
$$\alpha = \frac{\tan\theta}{\tan\theta_M}$$ **Normalized angle**

$$\beta = \frac{L'}{L}$$ **Actuator loading factor**

Hence it can be deduced that:

- the reactive force: $\tau_s = -\frac{\theta}{C}$ where C is the twist factor
- the equilibrium condition: $\tau_a + \tau_s = 0$
- and the (standardized) angle a, solution for a given tension.

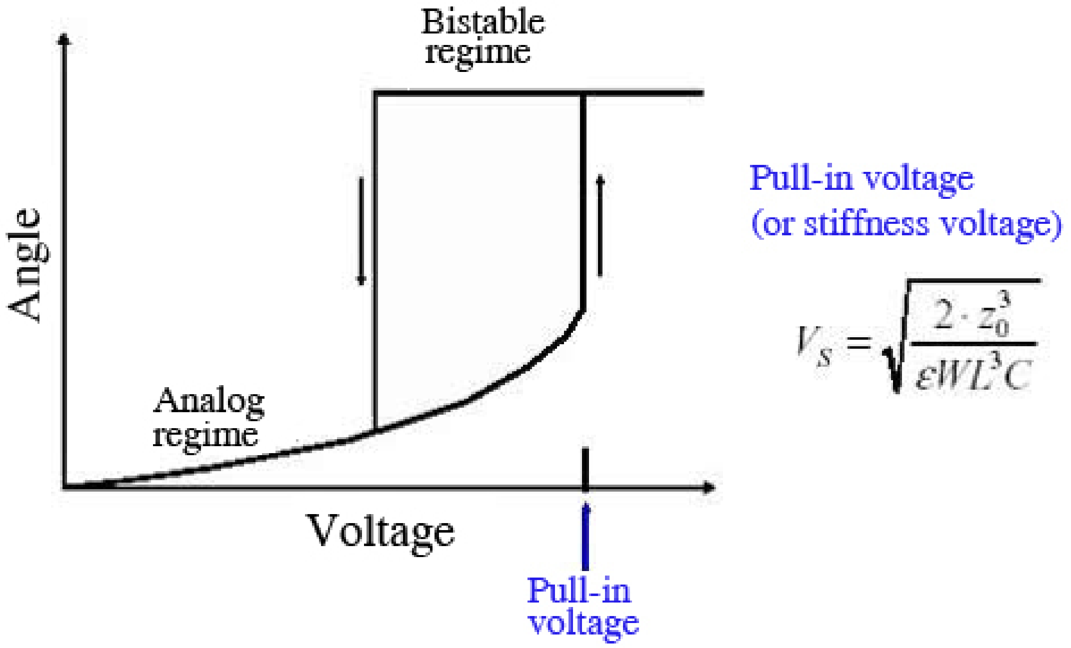
The rest points at the intersection of the curves corresponding to the electrostatic reactive force (the capacitor's capacity) and the mechanic reactive force (twist) can be found via a graphical solution:



- Low tension (curve A): two intersections appear, but only the smallest angle corresponds to a rest point

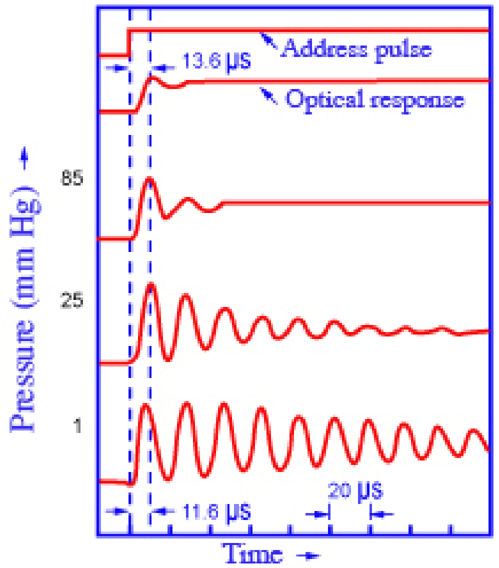
- Critical tension (curve B): the two curves are tangent and there is only one intersection, called the pull-in angle or snap-down angle
- High tension (curve C): There is no intersection and no stable solution

The characteristic of the mirrors' mechanism can then be deduced:

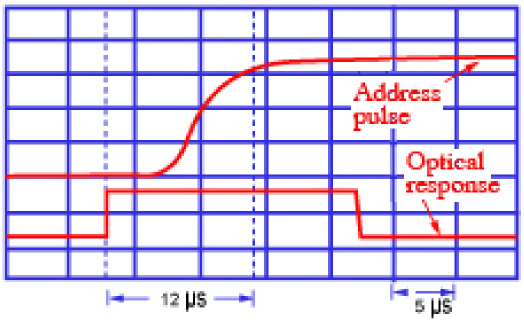


$$V_S = \sqrt{\frac{2 \cdot z_0^3}{\varepsilon W L^3 C}}$$

And the DMD✭'s response time:



Analog operation
Resonant frequency ~ 50kHz



Digital operation
Step response time ~ 12 µs

IV.Exercises

1. Knowledge Test

Please answer the three following questions.

Question 1

[*Solution n°1 p 43*]

Give the main reasons why MEMS✯ are especially useful for interacting with light.

Question 2

[*Solution n°2 p 43*]

Explain why silicon is the most often used material for microsystems.

Question 3

[*Solution n°3 p 43*]

Name the main advantages of optical microsystems.

Solution des exercices

>Solution n°1 *(exercice p. 42)*

There are four main points to the usefulness of MEMS for interacting with light

- the dimensions of the structures are in the range of optical wavelengths, which allows for remarkable optical properties,
- on this scale, a small shift can have significant effects (hence the usefulness for making optical switches);

$\Delta d \approx \frac{\lambda}{4}$

$\Delta \theta \approx$ qqs degrés

- photons do not have a mass;

Therefore, actuating devices do not need to use much force.

- MEMS✭ allow large-scale manufacturing of systems.

>Solution n°2 *(exercice p. 42)*

Why use silicon?

- This material is widely available and its properties are well documented,
- Monocrystalline silicon is particularly pure,
- Multiple micro-manufacturing processes have been developed and perfected to create devices with sub-micrometric precision,
- The silicon's anisotropy is interesting for micro-manufacturing: elective etchings can be realized using the proper crystallographic directions,
- Silicon is a highly piezoresistive material, which is interesting for making deformable structures,
- Silicon has better mechanical properties than metals, especially its good resistance to mechanical fatigue, reproducible elastic properties, no plastic zone...
- Technology identical to the one used for integrated circuits (miniaturization, mass manufacturing, existing equipment...) which allows integration of sensor and actuator functions with associated electronic circuits.

>Solution n°3 *(exercice p. 42)*

Assets of microsystems

- Use little space
- Usable for new applications (biomedical...)
- MOEMS✭ do not do not require much mechanical force
- optical phenomena only require small movements $-\lambda/4$
- compatibility with integrated circuits: the use of silicon notably allows integration of the source, of the detection, of the information processing a,d conditioning on the same chip compatible with integrated circuits
- miniaturization allows the creation of sensor or detector networks

- the small distance between elements which reduces the capacitive effect and the use of optical wavelengths also lead to :
    - reduction of response time and increase in broadband alongside with a reduction of manufacturing costs: the use of technology from microelectronics allows mass-producing (in parallel from a single wafer), the integration of several functions on a same chip and the million-times reproduction of a same device at a reduced cost
    - improvement of mechanical resistance due to very high resonance frequencies and the use of monocrystalline silicon in many cases

Signification des abréviations

- APCVD	Atmospheric Pressure Chemical Vapor Deposition
- CVD	Chemical Vapor Deposition
- DMD	Digital Micromirror Devices
- Ge	Germanium
- IC	Integrated Circuit
- LPCVD	Low Pressure Chemical Vapor Deposition
- MEMS	Micro-Electro-Mechanical Systems
- MOEMS	Micro-Optical-Electro-Mechanical Systems
- MOS	Metal-Oxide-Silicon
- PECVD	Plasma Enhanced Chemical Vapor Deposition
- PVD	Physical Vapor Deposition
- RF	Radio Frequency
- RIE	Reactive Ion Etching
- Si	Silicon
- SLM	Spatial Light Modulator
- SOI	Silicon On Insulator
- WDM	Wavelength Division Multiplexer

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