Moore & more than Moore

Péter Fürjes

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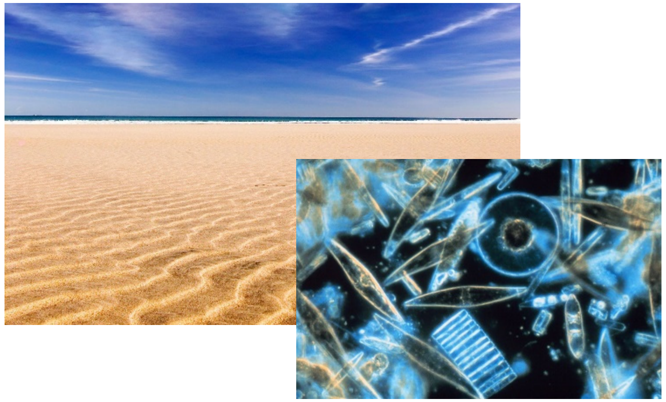
SILICON (silex)

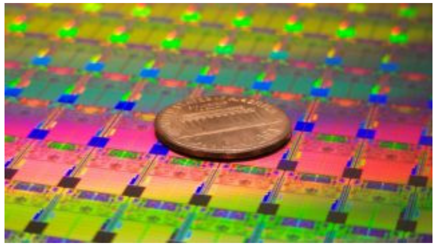
SILICON (silex)

Discoverer: Jons Berzelius
1823, Sweden

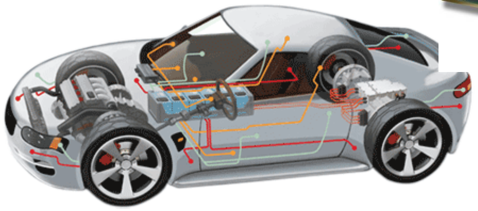
Natural presence:
granite, quartz, clay, sand

2nd in incidence in the Earth

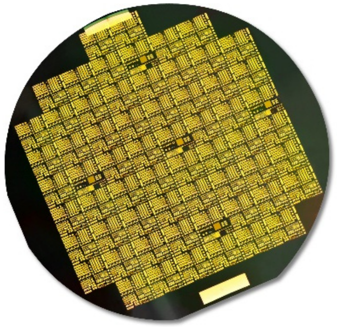


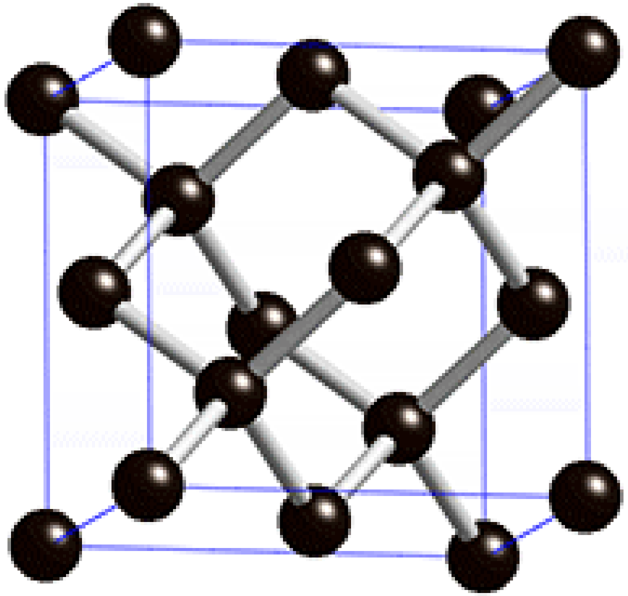


Other applications…



SILICON – as a chemical element





Properties: gray, metallic,
extremely hard material

Atomic number: 14 (1s2 2s2 2p6 / 3s2 3p2)

4th group / tetravalent metalloid

Crystal: similar to diamond

Electronic property: semiconductor

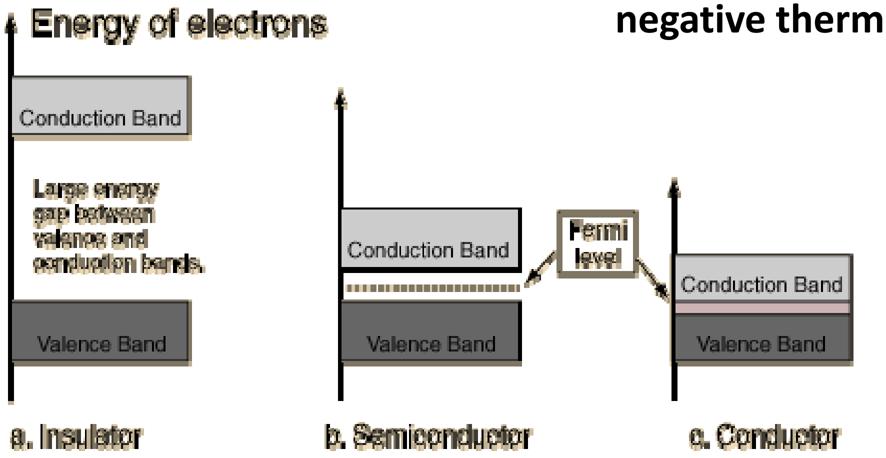
SEMICONDUCTORS

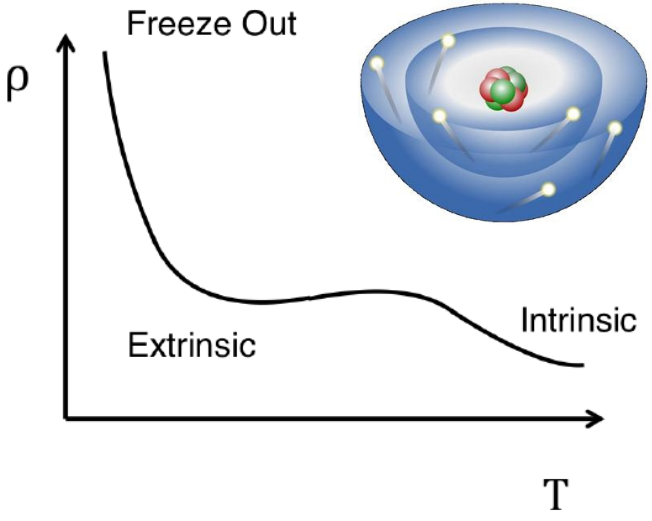
Resistance of semiconductors: $10^{-9} – 10^{3}$ 1/Ωcm

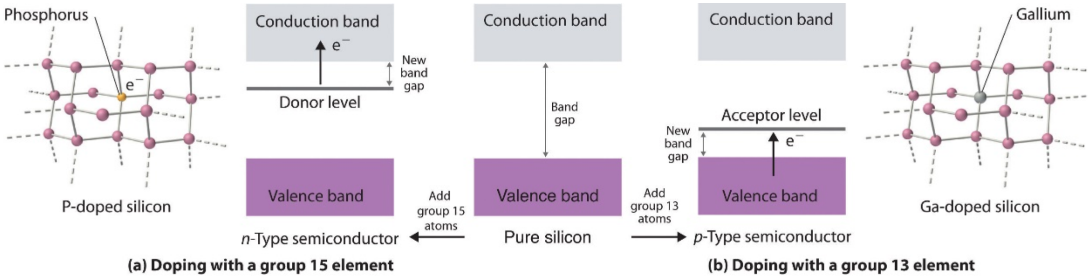
How does the resistance change with the temparature?

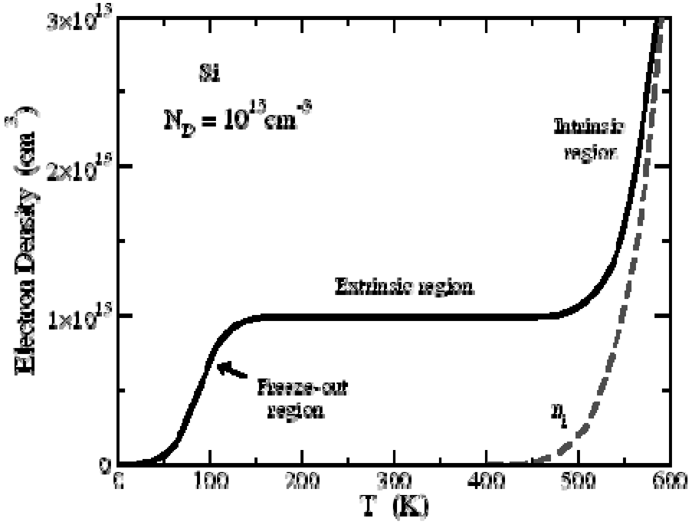
negative thermal coefficient

of resistance







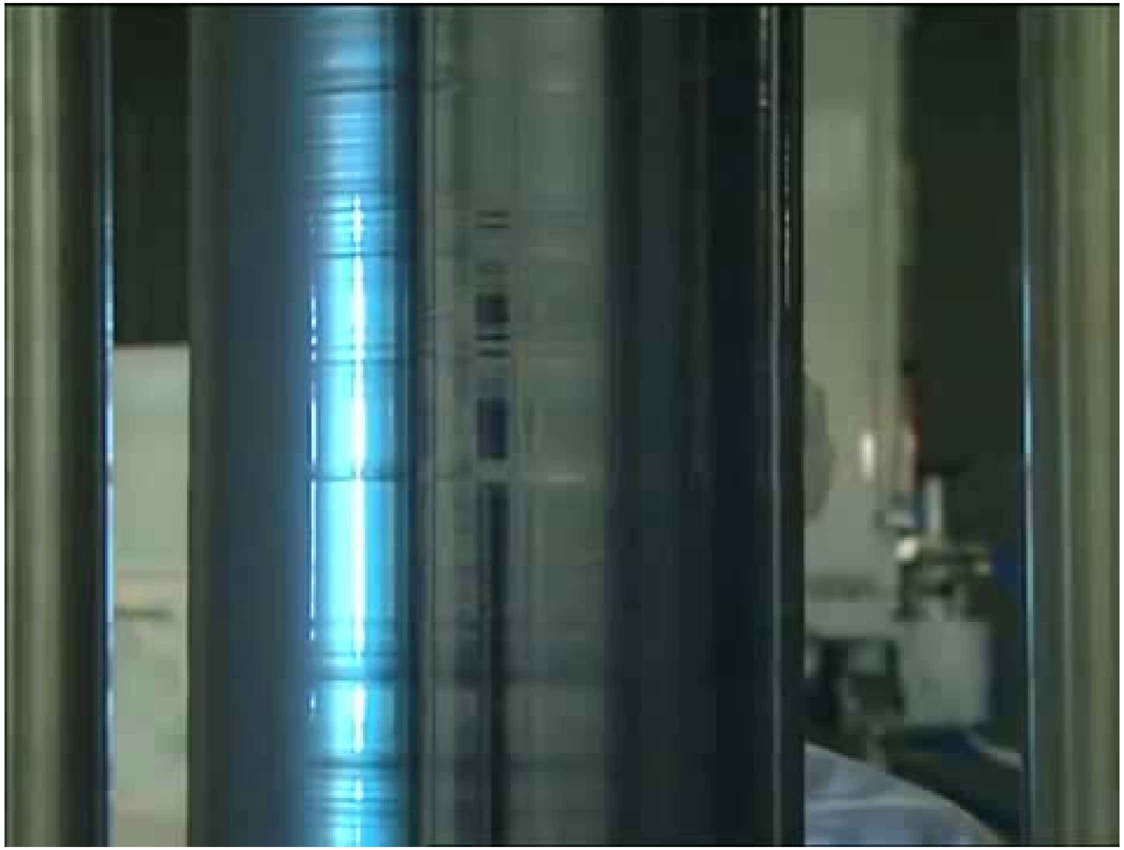


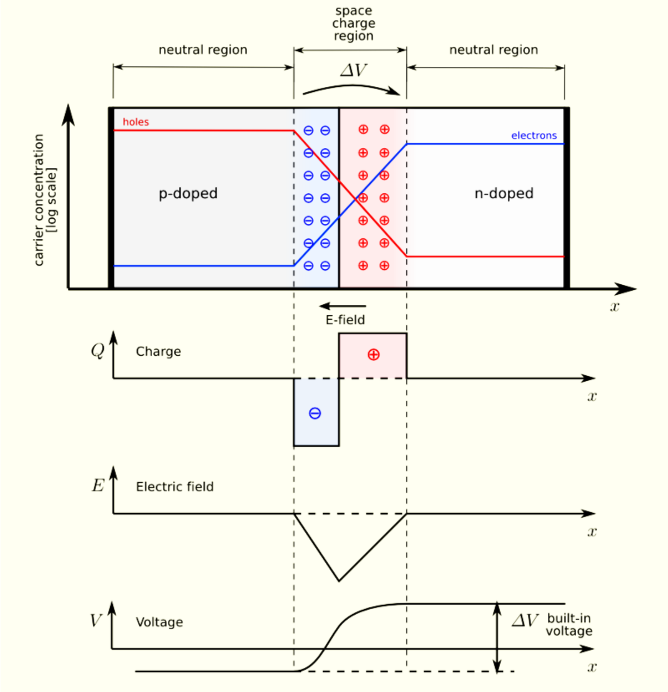
DIODE

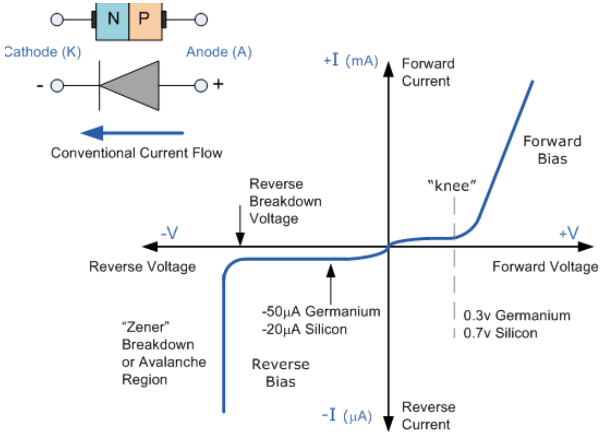
Dopped semiconductors:

n-type (electron conductance)

and p-type (hole conductance)

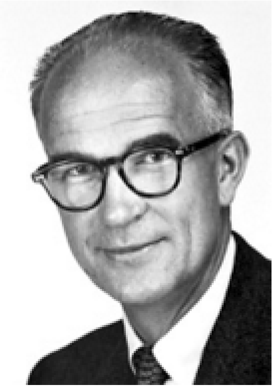






TRANSISTOR

The Nobel Prize in Physics 1956



William Bradford Shockley

Prize share: 1/3

John Bardeen

Prize share: 1/3

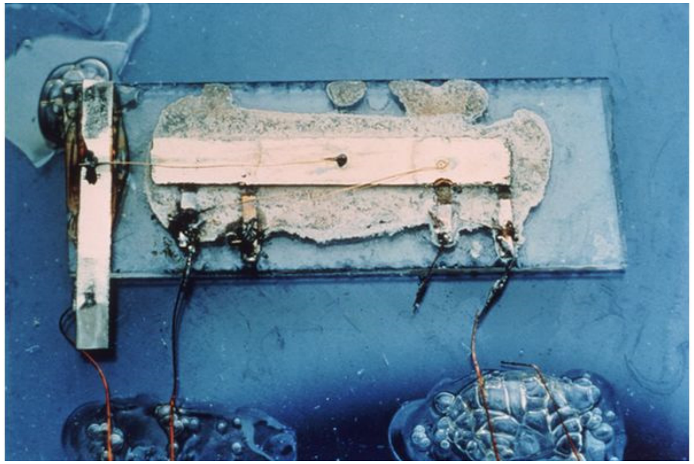
Walter Houser Brattain

Prize share: 1/3

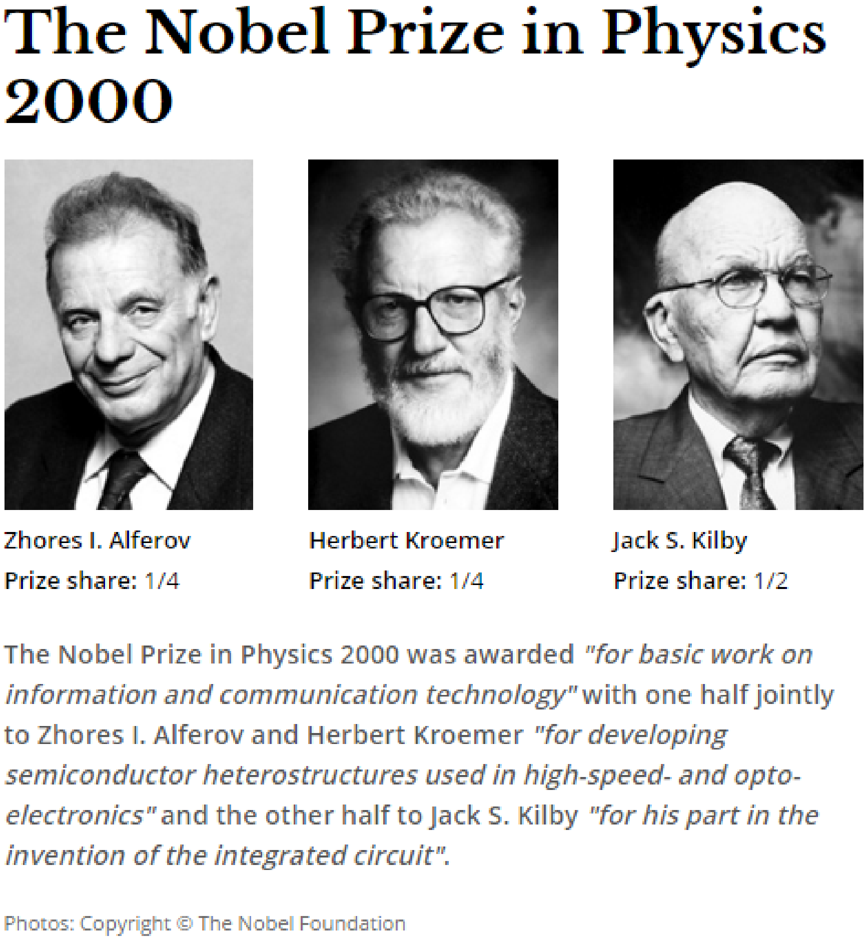
The Nobel Prize in Physics 1956 was awarded jointly to William Bradford Shockley, John Bardeen and Walter Houser Brattain *"for their researches on semiconductors and their discovery of the transistor effect".*

Substitution of vacuum (electron) tube
Functions: switching / amplication / voltage stabilisation

The FIRST INTEGRATED CIRCUIT



- Transistor: solution for the problems of the vacuum (electron) tube (dissipation, relability).
- Solution for connecting discrete devices (space saving).



The Nobel Prize in Physics 2000

Zhores I. Alferov	Herbert Kroemer	Jack S. Kilby
Prize share: 1/4	Prize share: 1/4	Prize share: 1/2

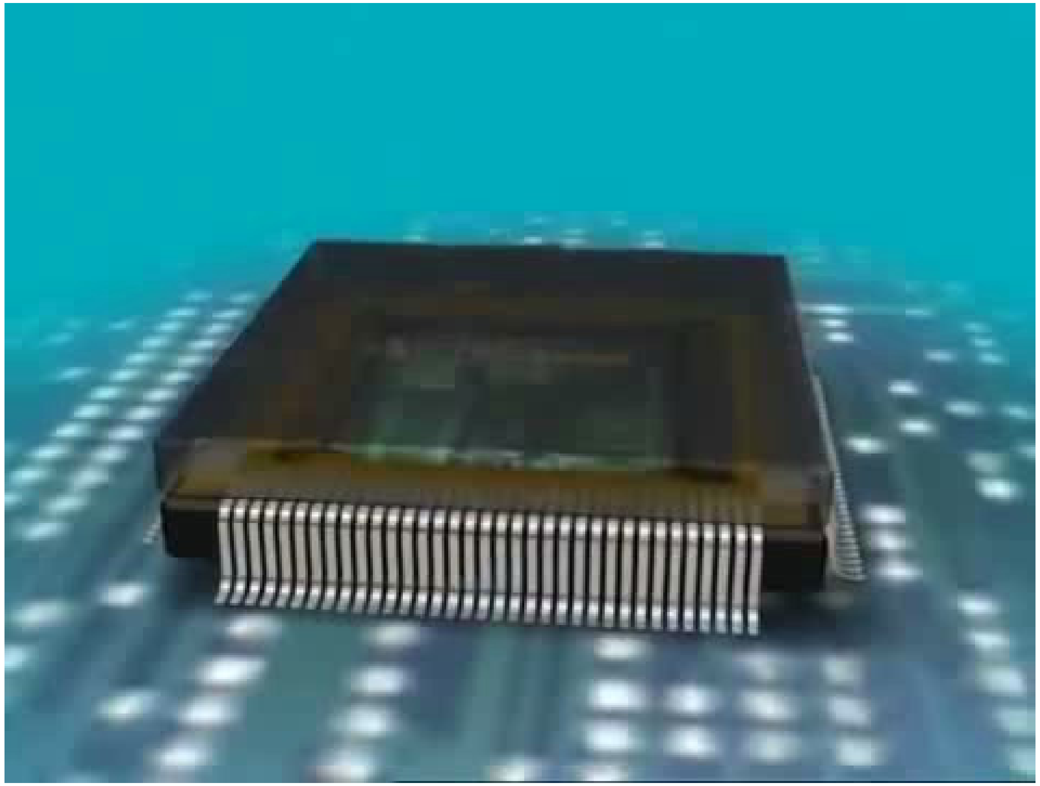
The Nobel Prize in Physics 2000 was awarded *"for basic work on information and communication technology"* with one half jointly to Zhores I. Alferov and Herbert Kroemer *"for developing semiconductor heterostructures used in high-speed- and opto-electronics"* and the other half to Jack S. Kilby *"for his part in the invention of the integrated circuit"*.

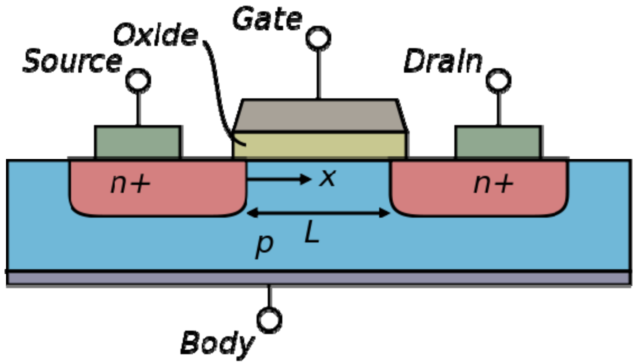
Photos: Copyright © The Nobel Foundation

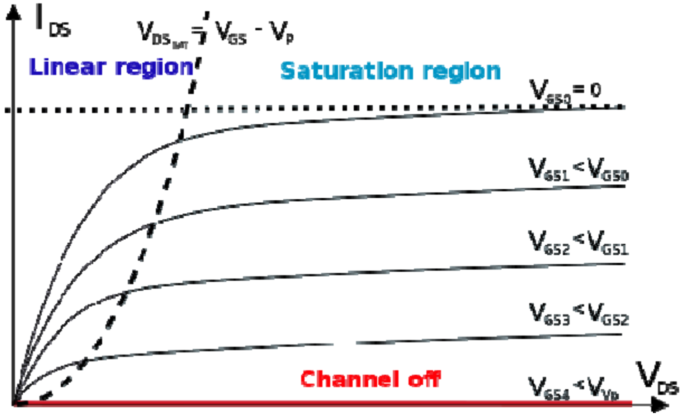
FIELD EFFECT TRANSISTOR (FET)

Main building block of CPU and memory

Functions: amplification (analog signals), switching





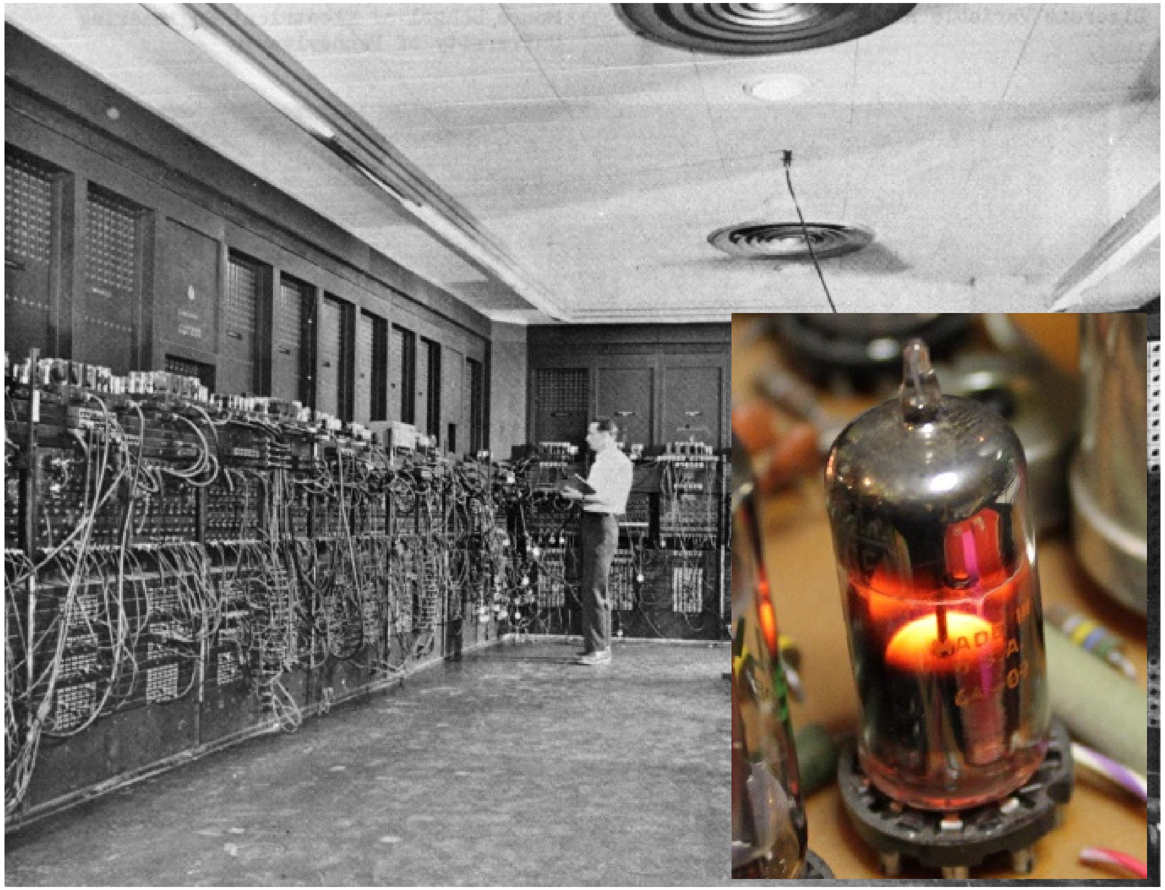


COMPUTATION

The FIRST COMPUTER

Von Neumann, János (1903-1957)

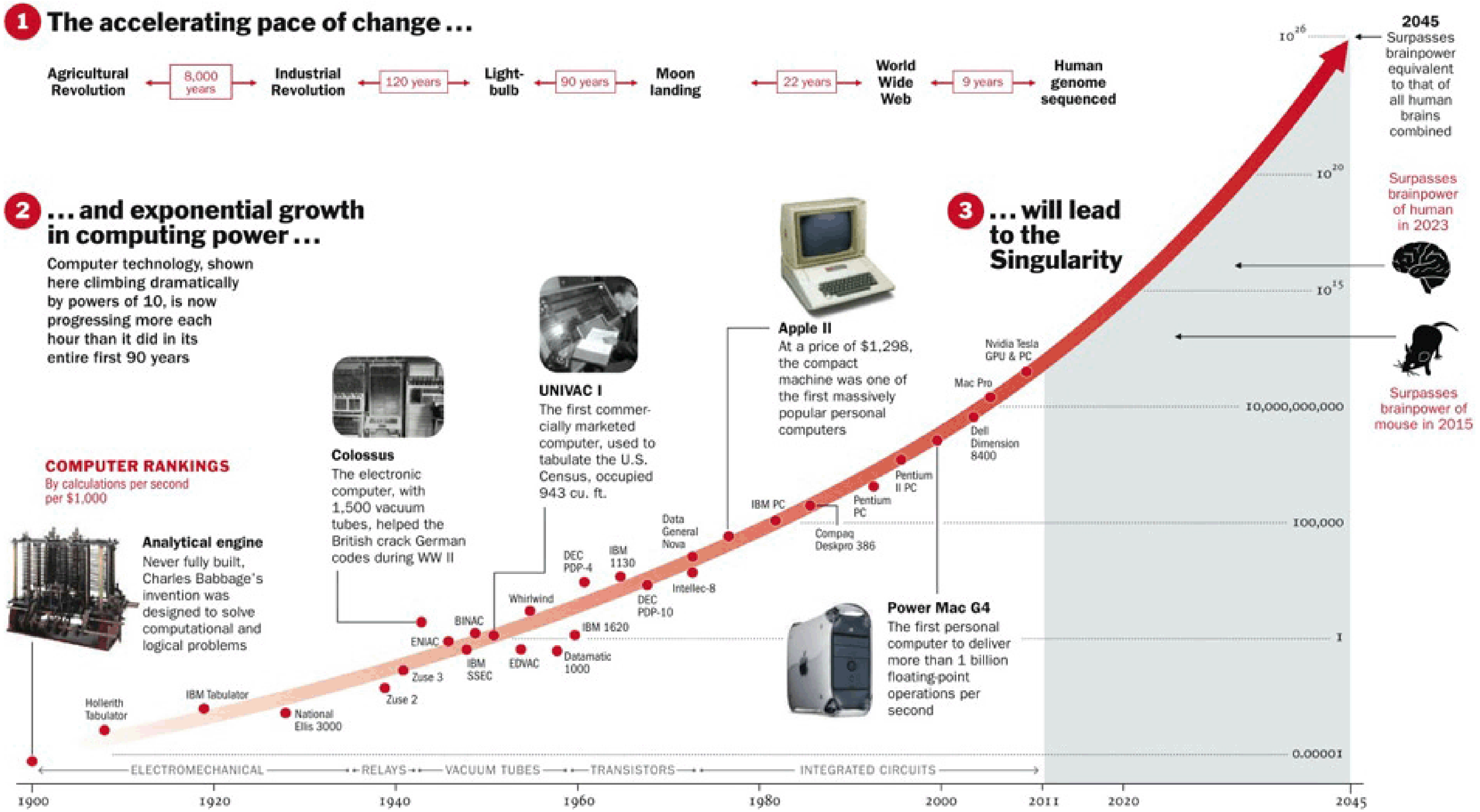
ENIAC



Development of the logical architecture of the electronic computers, based on the binary system.

Basic elements: memory, program storage, command system

DEVELOPMENT of THE COMPUTATIONAL CAPACTY



1 The accelerating pace of change …

2 … and exponential growth in computing power …

Computer technology, shown here climbing dramatically by powers of 10, is now progressing more each hour than it did in its entire first 90 years

3 … will lead to the Singularity

COMPUTER RANKINGS
By calculations per second per $1,000

Analytical engine
Never fully built, Charles Babbage's invention was designed to solve computational and logical problems

Colossus
The electronic computer, with 1,500 vacuum tubes, helped the British crack German codes during WW II

UNIVAC I
The first commercially marketed computer, used to tabulate the U.S. Census, occupied 943 cu. ft.

Apple II
At a price of $1,298, the compact machine was one of the first massively popular personal computers

Power Mac G4
The first personal computer to deliver more than 1 billion floating-point operations per second

2045
Surpasses brainpower equivalent to that of all human brains combined

Surpasses brainpower of human in 2023

Surpasses brainpower of mouse in 2015

MOORE LAW

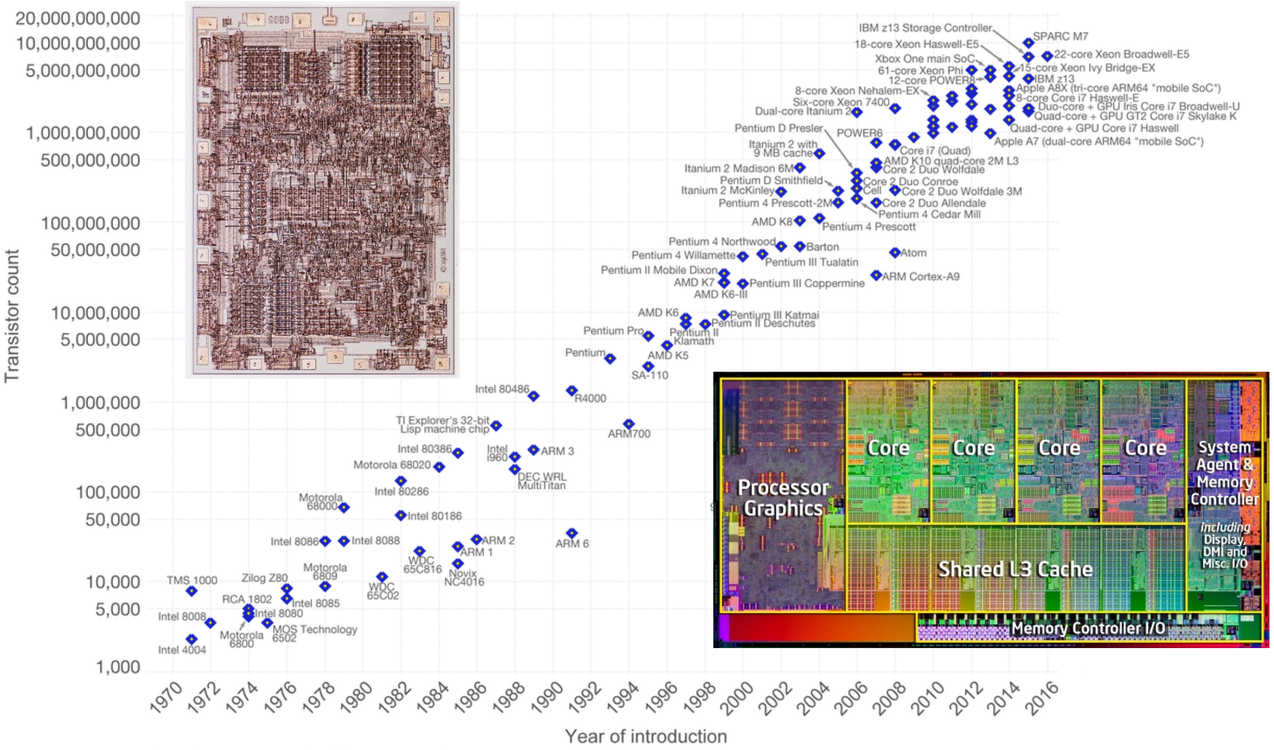
HOW MANY TRANSISTOR CAN BE PLACED ON A CHIP?

Gordon Moore (1965)

Moore's Law – The number of transistors on integrated circuit chips (1971-2016)

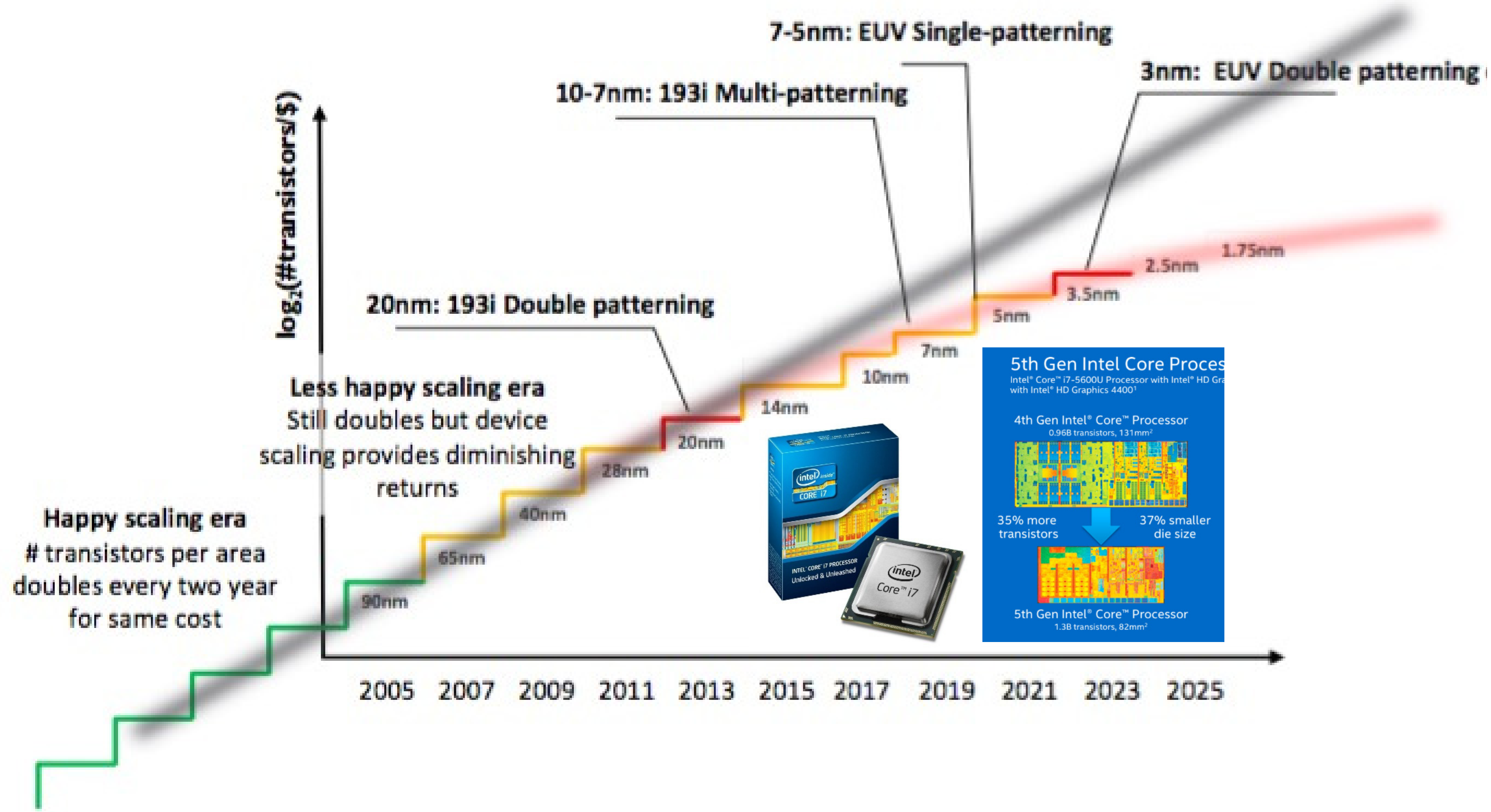
Our World in Data

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore's law.



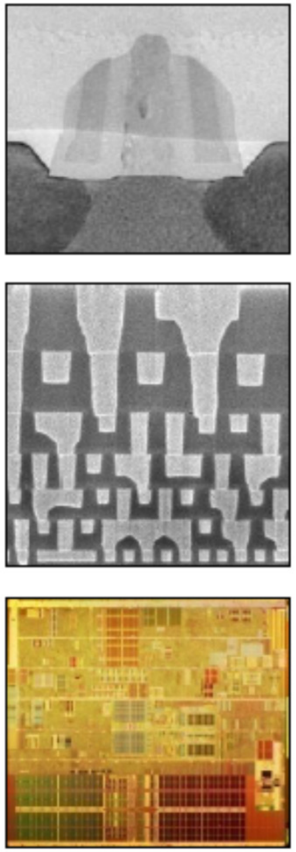
Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

TECHNOLOGY DEVELOPMENT

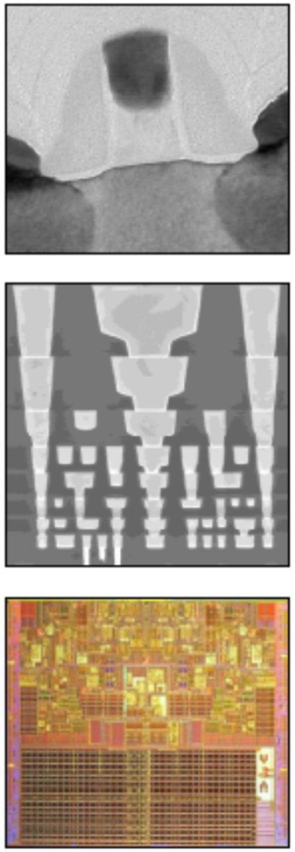


INTEL 2003 - 2011

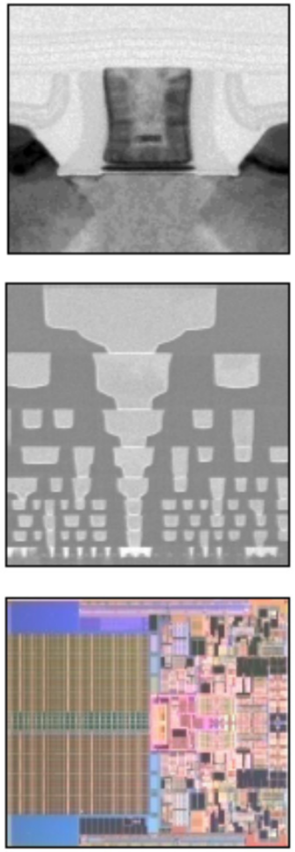
90 nm
2003



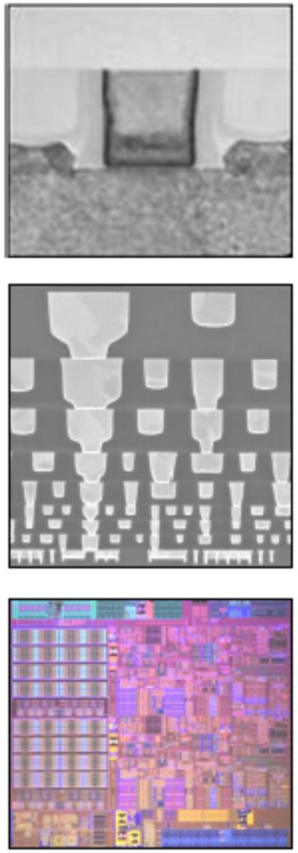
65 nm
2005



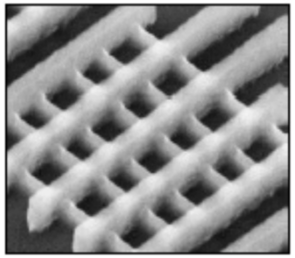
45 nm
2007



32 nm
2009



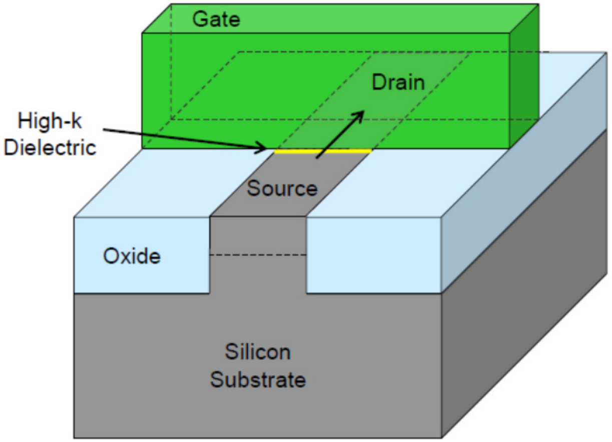
22 nm
2011

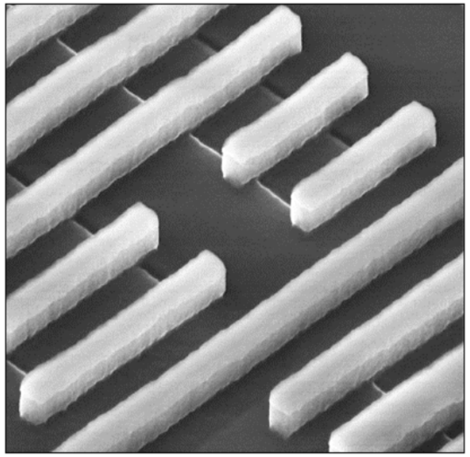


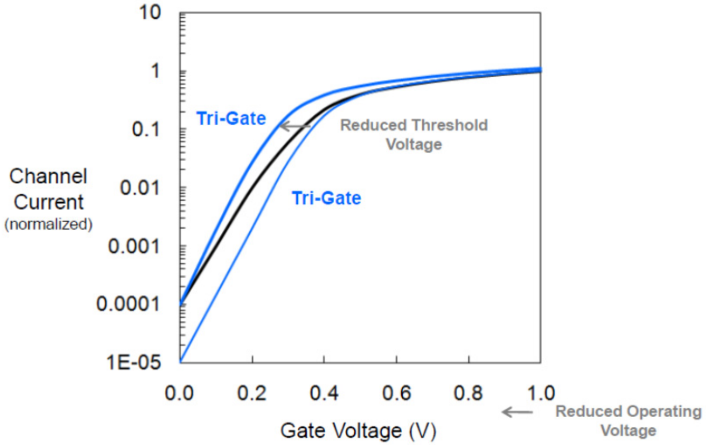
3D TRI-GATE transistor

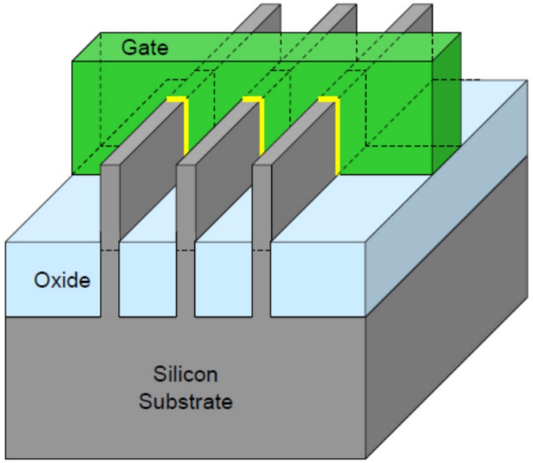
TECHNOLOGY: from SAND to PROCESSOR

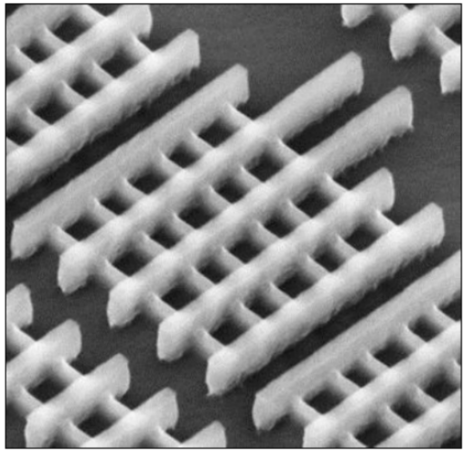
PLANAR vs. 3D TRANSISTOR

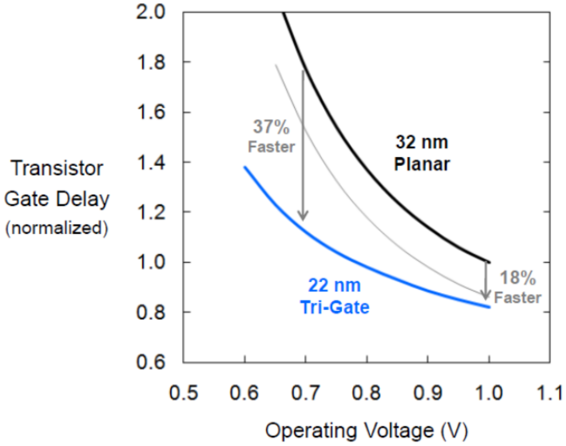






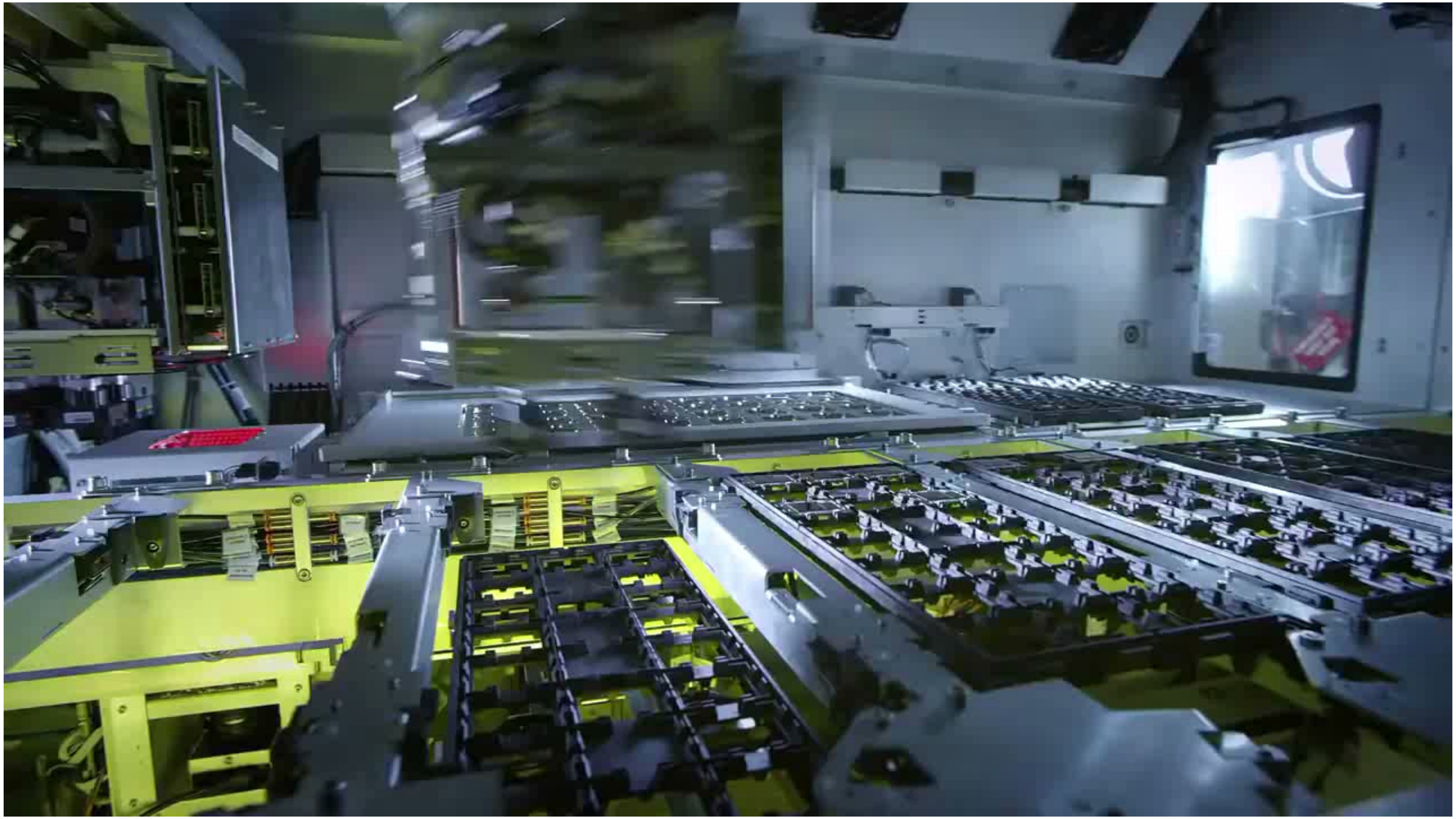






TECHNOLOGY: from SAND to PROCESSOR (2011)

INFRASTRUCTURE – MICRO / NANO – INTEL FAB



MORE THAN MOORE

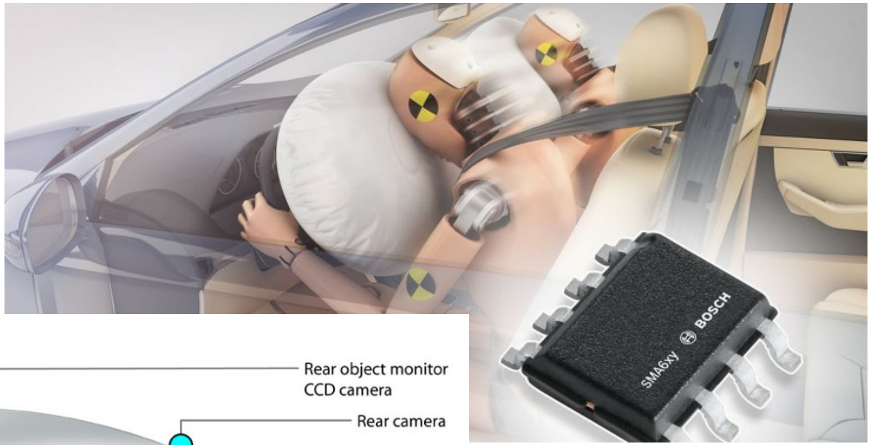
MEMS:
Revolution of SENSORS

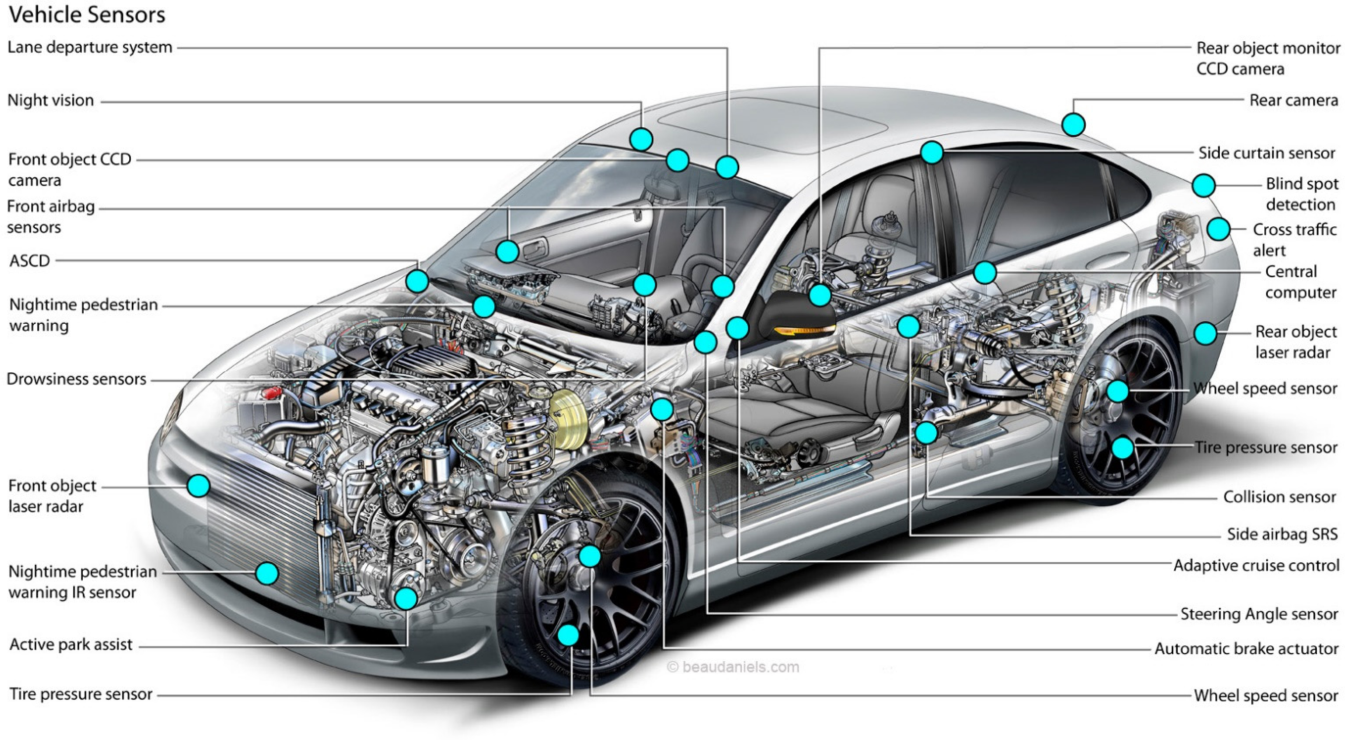
MEMS: SI (SOLID STATE) MICROSENSORS

MEMS: micro-electromechanical systems

Example: automotive applications

- Engine / gear diagnostics and control
- Life- and trafic safety
- Comfort





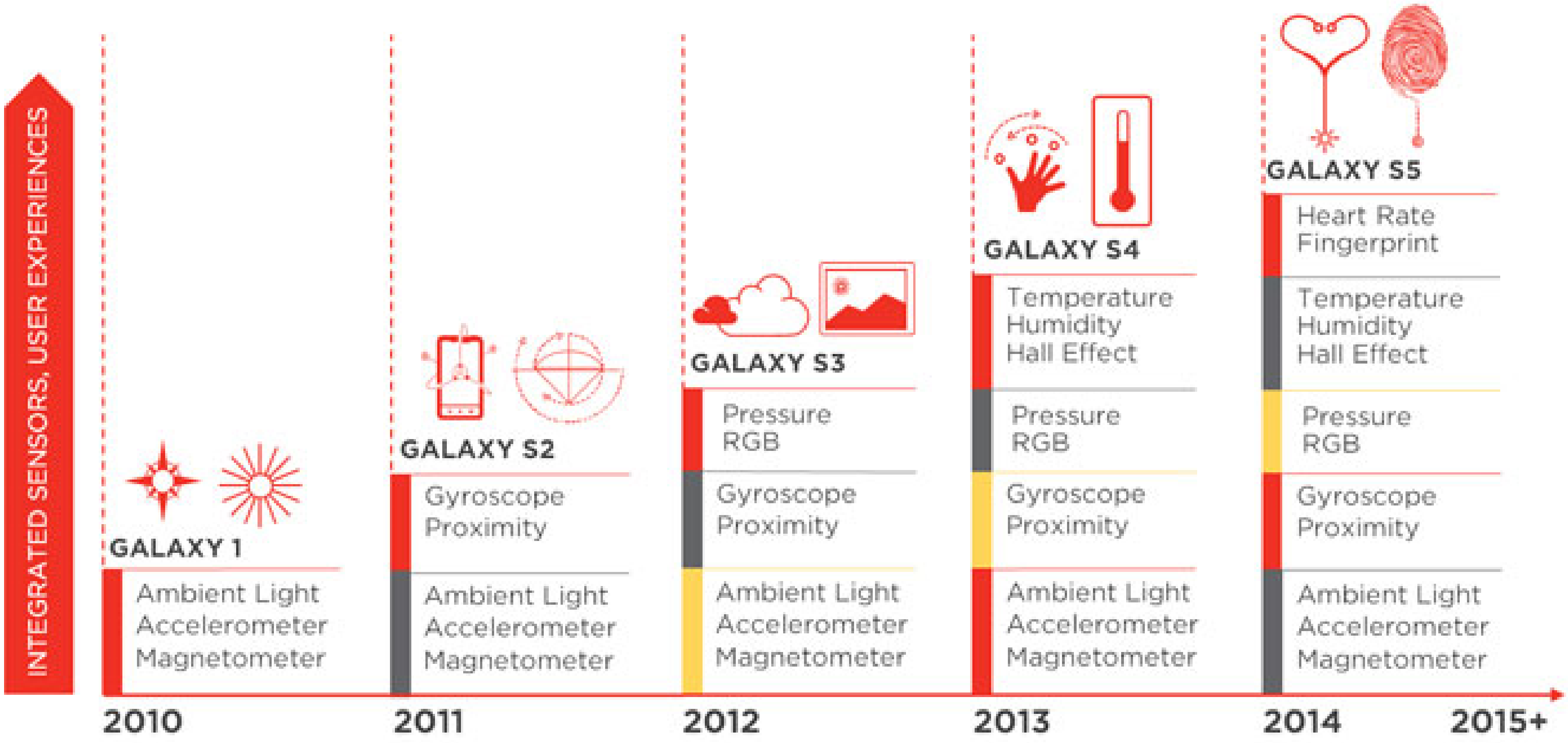
GUESS WHO?

Steve Jobs

APPLE

DISASSEBLE OUR VIRTUAL SMARTPHONE

SENSOR GROWTH IN SMARTPHONES



INTEGRATED SENSORS, USER EXPERIENCES

2010 – GALAXY 1
- Ambient Light
- Accelerometer
- Magnetometer

2011 – GALAXY S2
- Gyroscope
- Proximity
- Ambient Light
- Accelerometer
- Magnetometer

2012 – GALAXY S3
- Pressure
- RGB
- Gyroscope
- Proximity
- Ambient Light
- Accelerometer
- Magnetometer

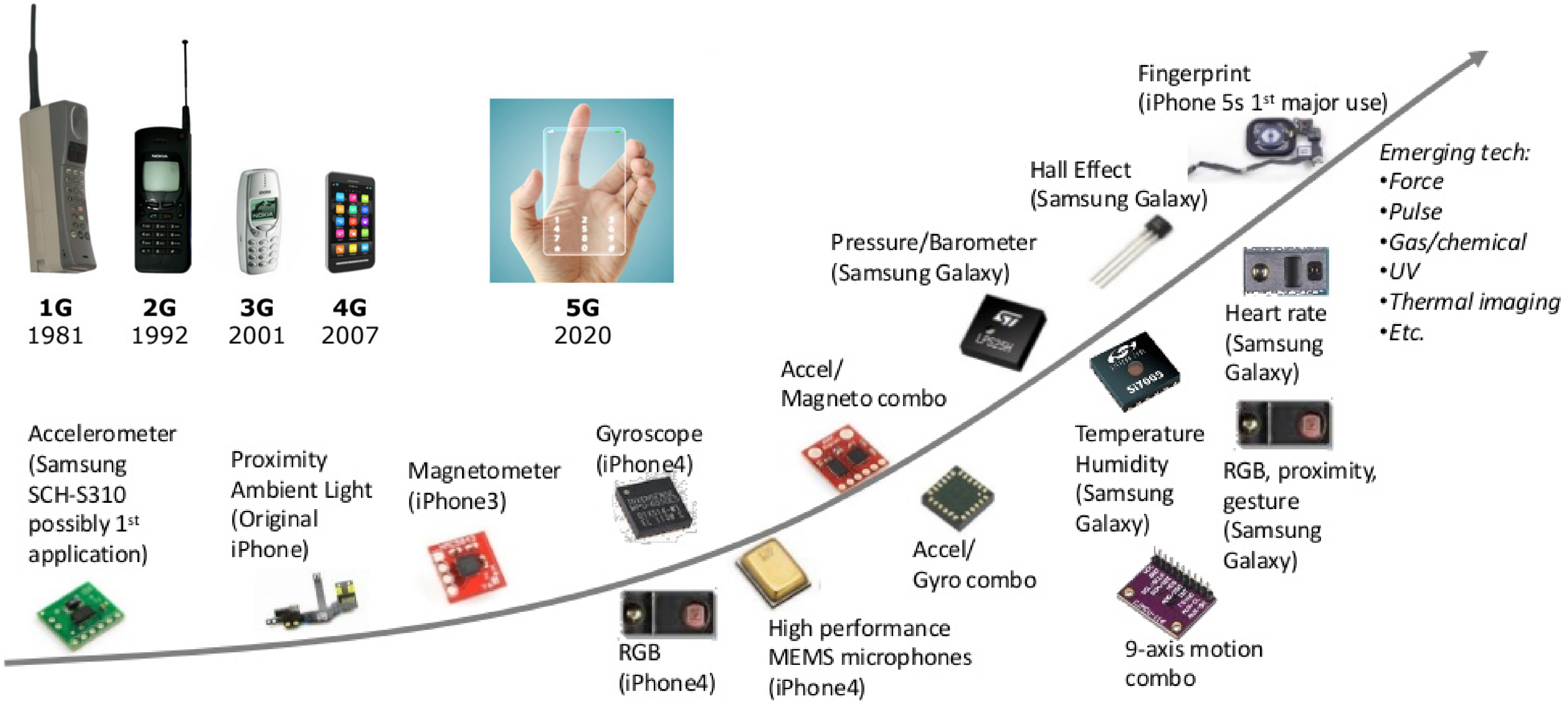
2013 – GALAXY S4
- Temperature
- Humidity
- Hall Effect
- Pressure
- RGB
- Gyroscope
- Proximity
- Ambient Light
- Accelerometer
- Magnetometer

2014 – GALAXY S5
- Heart Rate
- Fingerprint
- Temperature
- Humidity
- Hall Effect
- Pressure
- RGB
- Gyroscope
- Proximity
- Ambient Light
- Accelerometer
- Magnetometer

2015+

Sources: Driven by Apple and Samsung, Light Sensors Achieve Double-Digit Revenue Growth, IHS, June 30, 2013; MEMS: Looking back at 2014 and 5 years outlook, IHS, November 2014; Light and Proximity Sensors - A Market Ready for Explosive Growth, Tony Rizzo, Mobility TechZone, July 30, 2013; iPhone 6 Teardown, iFixit, 2014; Apple 3G iPhone Teardown Report, Portelligent, 2008; MEMS Microphone Market Tops 2 Billion Units, Mobile Dev Design, March 4, 2013

SMARTPHONE'S FUTURE



1G 1981

2G 1992

3G 2001

4G 2007

5G 2020

Accelerometer (Samsung SCH-S310 possibly 1st application)

Proximity Ambient Light (Original iPhone)

Magnetometer (iPhone3)

Gyroscope (iPhone4)

RGB (iPhone4)

High performance MEMS microphones (iPhone4)

Accel/ Magneto combo

Accel/ Gyro combo

Pressure/Barometer (Samsung Galaxy)

Hall Effect (Samsung Galaxy)

Temperature Humidity (Samsung Galaxy)

9-axis motion combo

Fingerprint (iPhone 5s 1st major use)

Heart rate (Samsung Galaxy)

RGB, proximity, gesture (Samsung Galaxy)

Emerging tech:
- *Force*
- *Pulse*
- *Gas/chemical*
- *UV*
- *Thermal imaging*
- *Etc.*

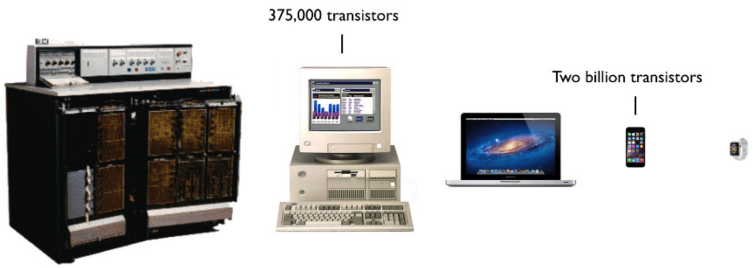
2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015+

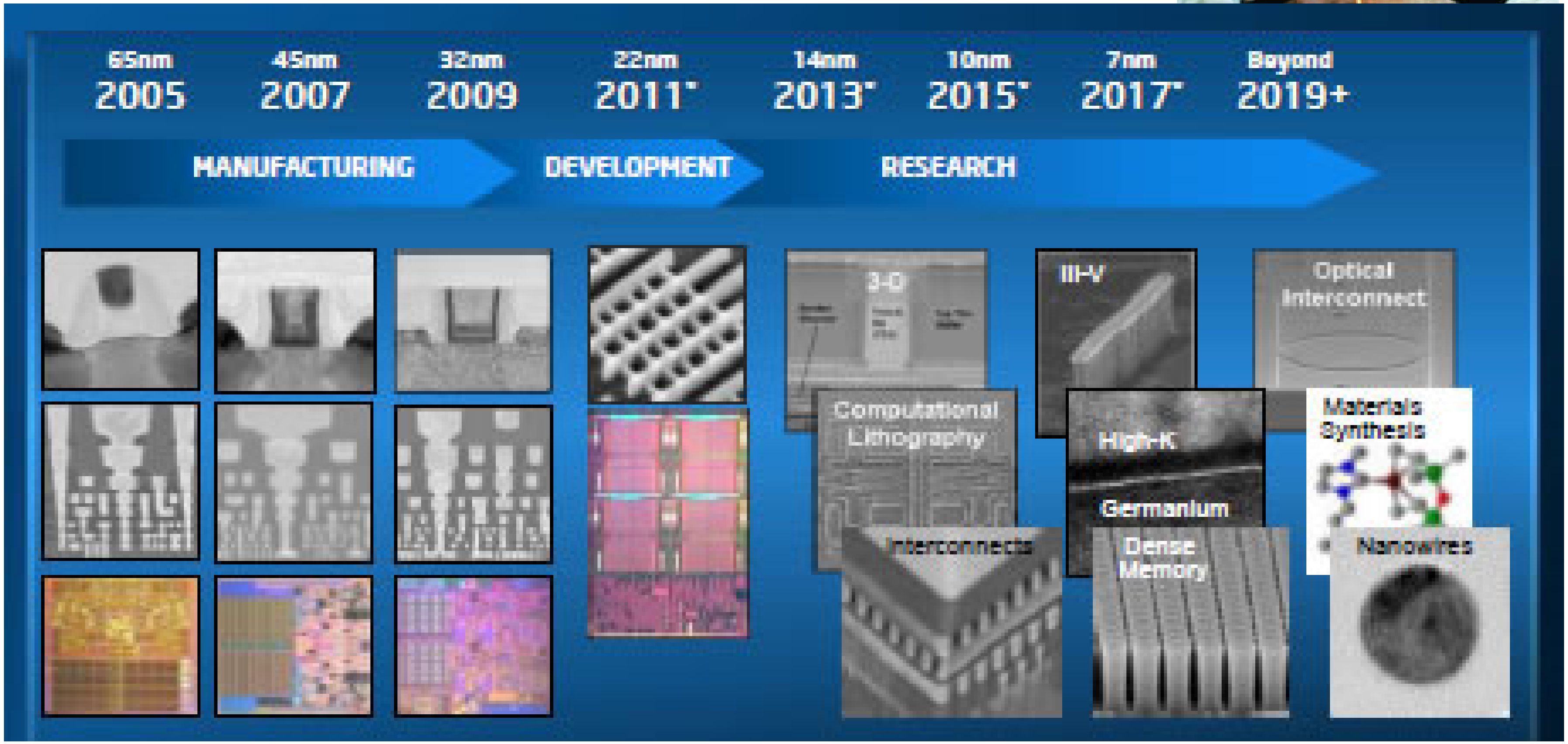
Apple iPhone introduced with 3 sensors

Samsung Galaxy has more than 10 sensors, most of any phone on market

Sources: This little motion sensor went to the market..., Sonja Thompson, IT News Digest, March 22, 2007; Willie D. Jones, IEEE Spectrum, A Compass in Every Smartphone, January 29, 2010; Consumers boost MEMS combo sensors, Electronic Product Design and Test, March 19, 2014; Samsung Turns up the Pressure on Competition with Pressure Sensor in Galaxy S4, IHS, March 20, 2013; Behind the sixth sense of smartphones: the Snapdragon processor sensor engine, Qualcomm, April 24, 2014; MEMS for Cell Phones & Tablets, Yole Developpement, May 2012; Fairchild, Emergence of a $Trillion MEMS Sensor Market, SensorCon, 2012; MEMS Microphone Market Tops 2 Billion Units, Mobile Dev Design, March 4, 2013

BEYOND MOORE LAW ???



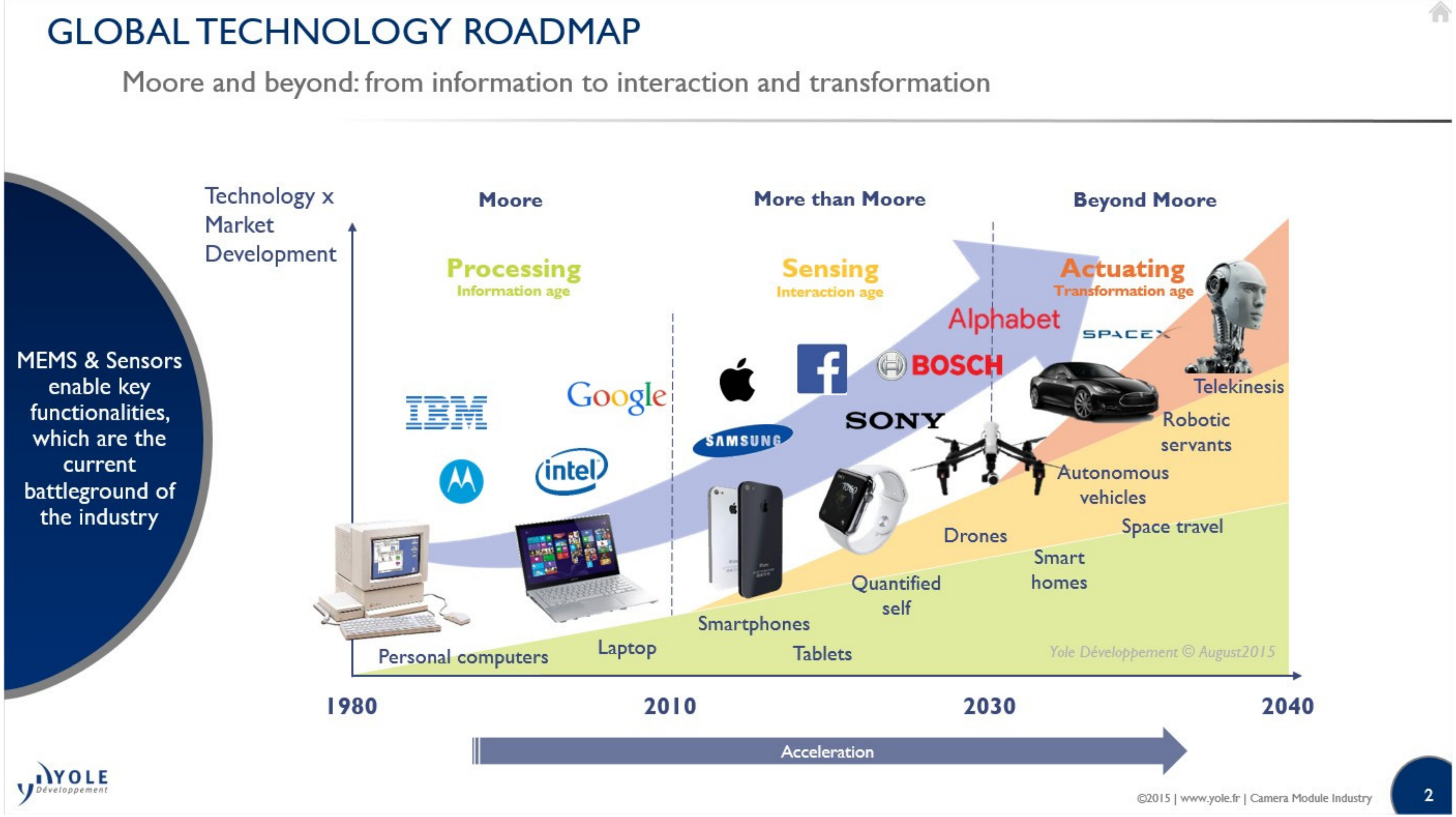


65nm	45nm	32nm	22nm	14nm	10nm	7nm	Beyond
2005	2007	2009	2011*	2013*	2015*	2017*	2019+

MANUFACTURING
DEVELOPMENT
RESEARCH

3-D
III-V
Optical Interconnect
Computational Lithography
High-K
Germanium
Materials Synthesis
Interconnects
Dense Memory
Nanowires

BEYOND MORE THAN MOORE ???



GLOBAL TECHNOLOGY ROADMAP

Moore and beyond: from information to interaction and transformation

MEMS & Sensors enable key functionalities, which are the current battleground of the industry

©2015 | www.yole.fr | Camera Module Industry

2

MICROMACHINING TECHNOLOGY

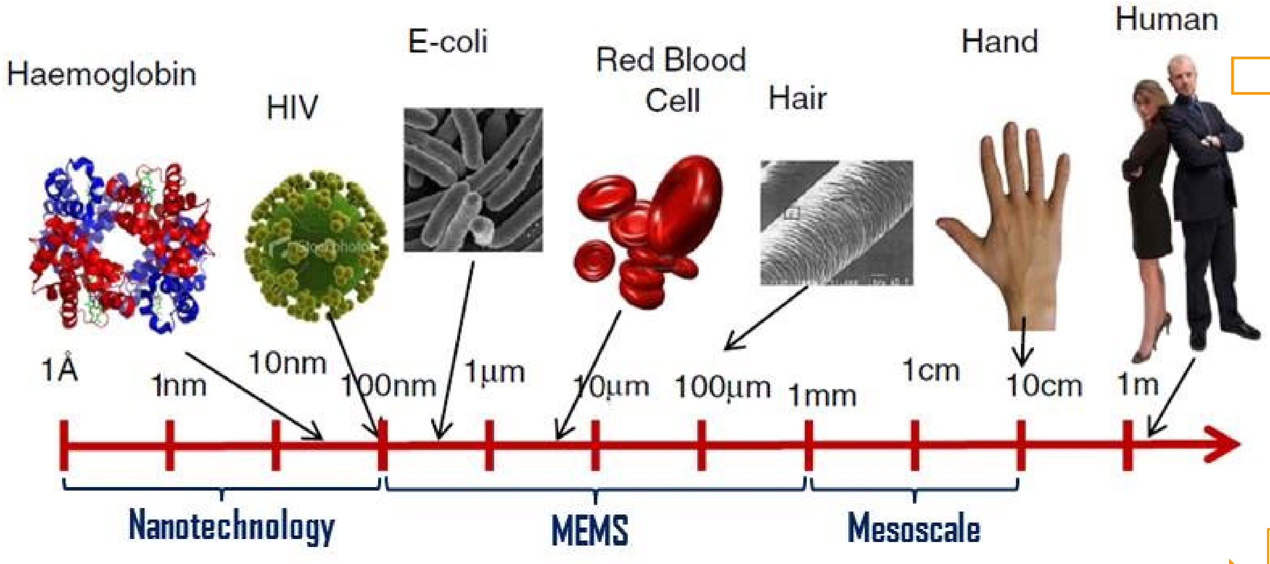
Péter Fürjes

E-mail: furjes@mfa.kfki.hu

MEMS / BIOMEMS - DEFINITION

MEMS: Micro-ElectroMechanical Systems

Miniaturised devices and systems: in the range between 100nm and 1000µm



- High sensitivity
- Low power consumption
- Integrability

Batch processes

Low costs

Fabrication technology: SILICON micromachining

- Photolithography
- Physical and chemical layer deposition (metals, dielectrics)
- Wet and dry etching

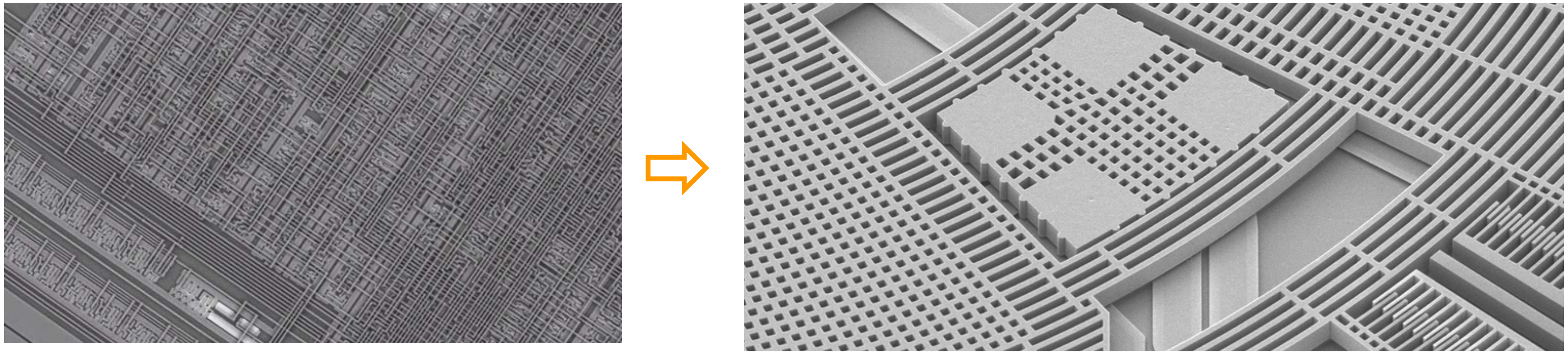
SolidState Technology, Ramesh Ramadoss, MEMS devices for biomedical applications
http://electroiq.com/blog/2013/10/mems-devices-for-biomedical-applications/

MICROMECHANICS

MICROMECHANICS

MEMS: „2D” IC technology ⇨ 3D structures

- membranes, suspended structures, movable elements,
- microfluidic applications: channels, chambers, reactors etc.



Microfabrications:

- processes and devices: different from traditional mechanical fabrication technologies
- mainly „dry” and „wet” chemical etching and electrochemical methods,
  BUT classic processes (laser or diamond blade cutting)

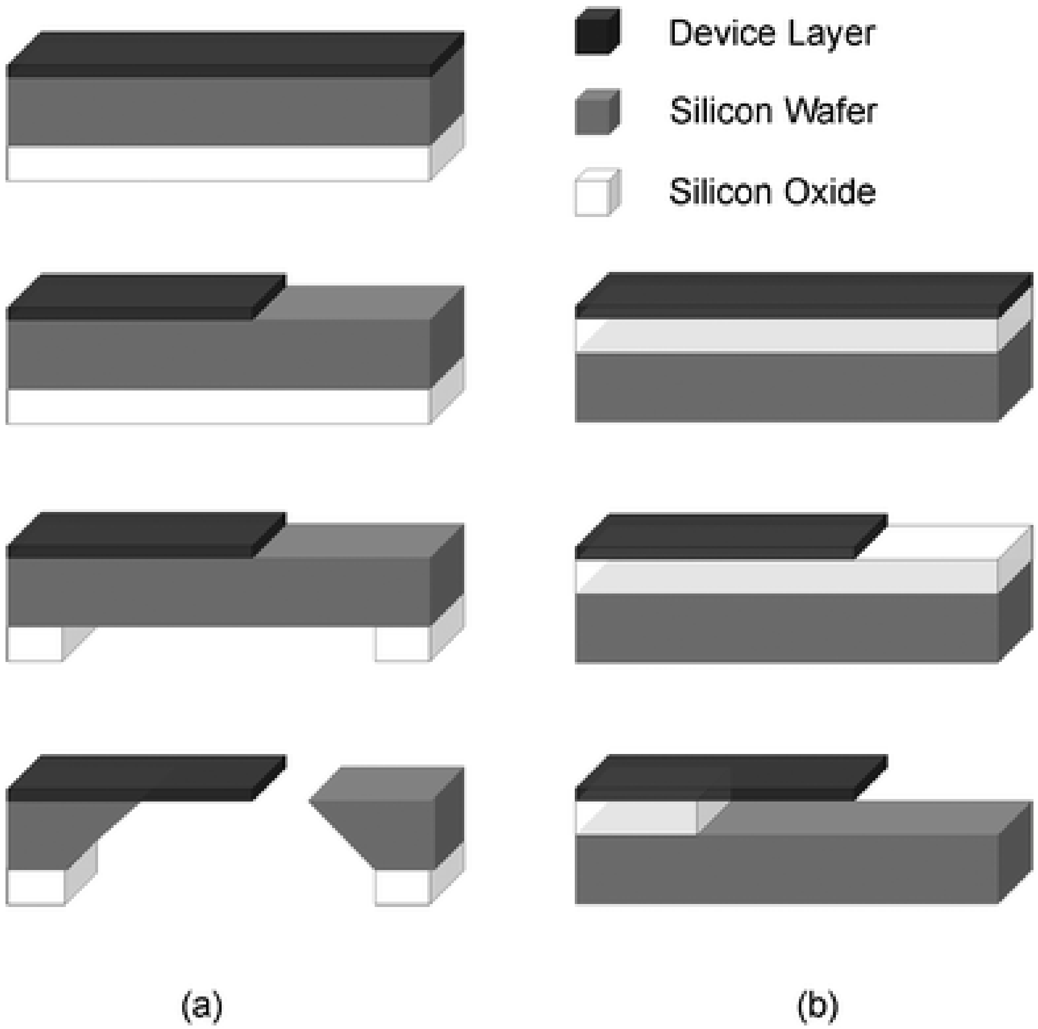
Typical dimensions: 1-500 mm
Thickness of the Si crystal: 380-500-1000 mm

BULK vs. SURFACE MICROMACHINING

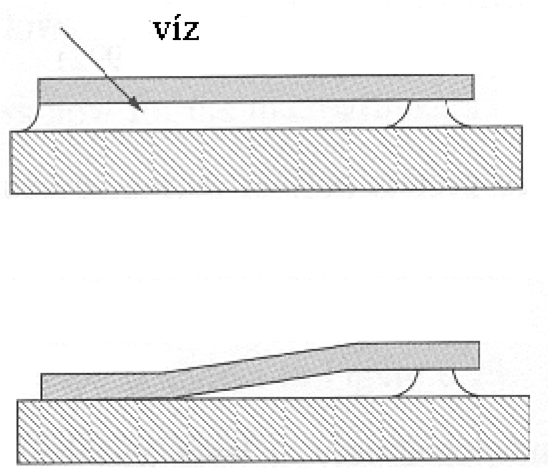
	Bulk	**Surface**
Dimensions	2-3 μm < a < 100-500 μm	a < 2-3 μm
Thermal isolation	+	-
Mechanical stability	+	-
Membranes	Single crystalline	amorphous or polycrystalline

3rd solution: Thin single crystalline layers: ”Smart Cut” / SOI (silicon-on-insulator)

BULK vs. SURFACE MICROMACHINING

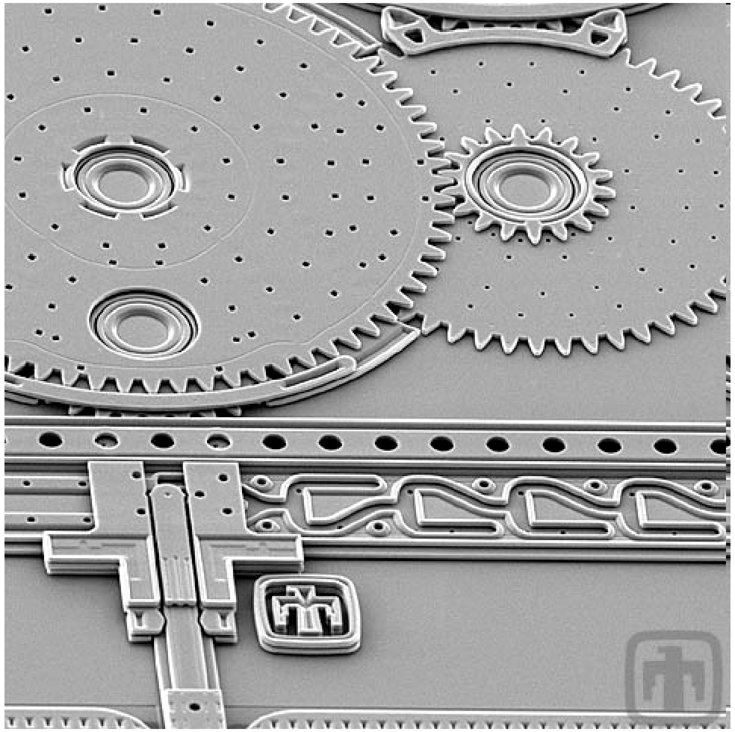


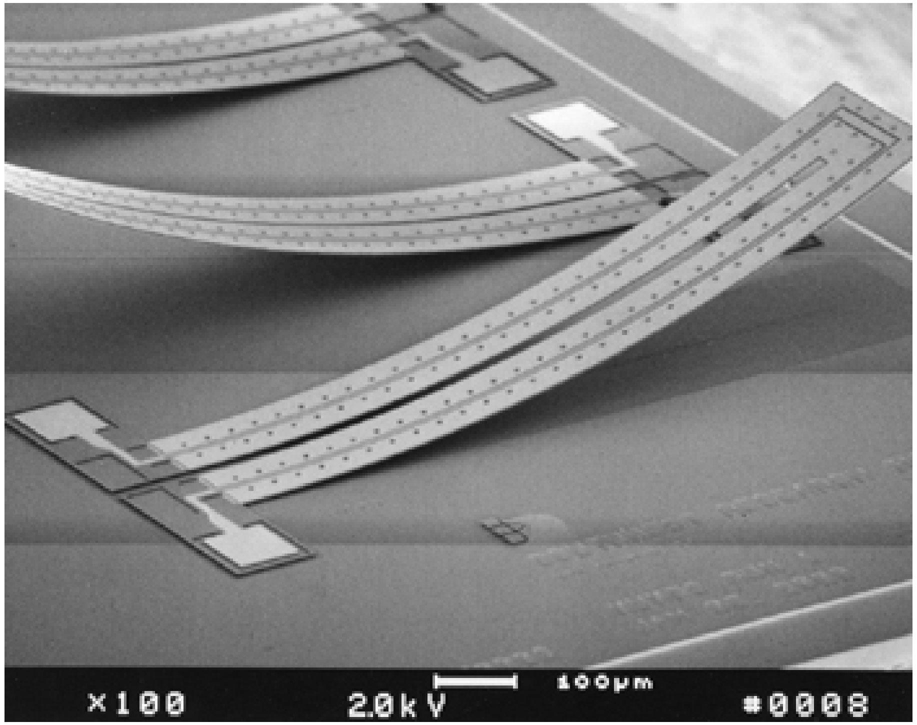
Typical problem: sticking



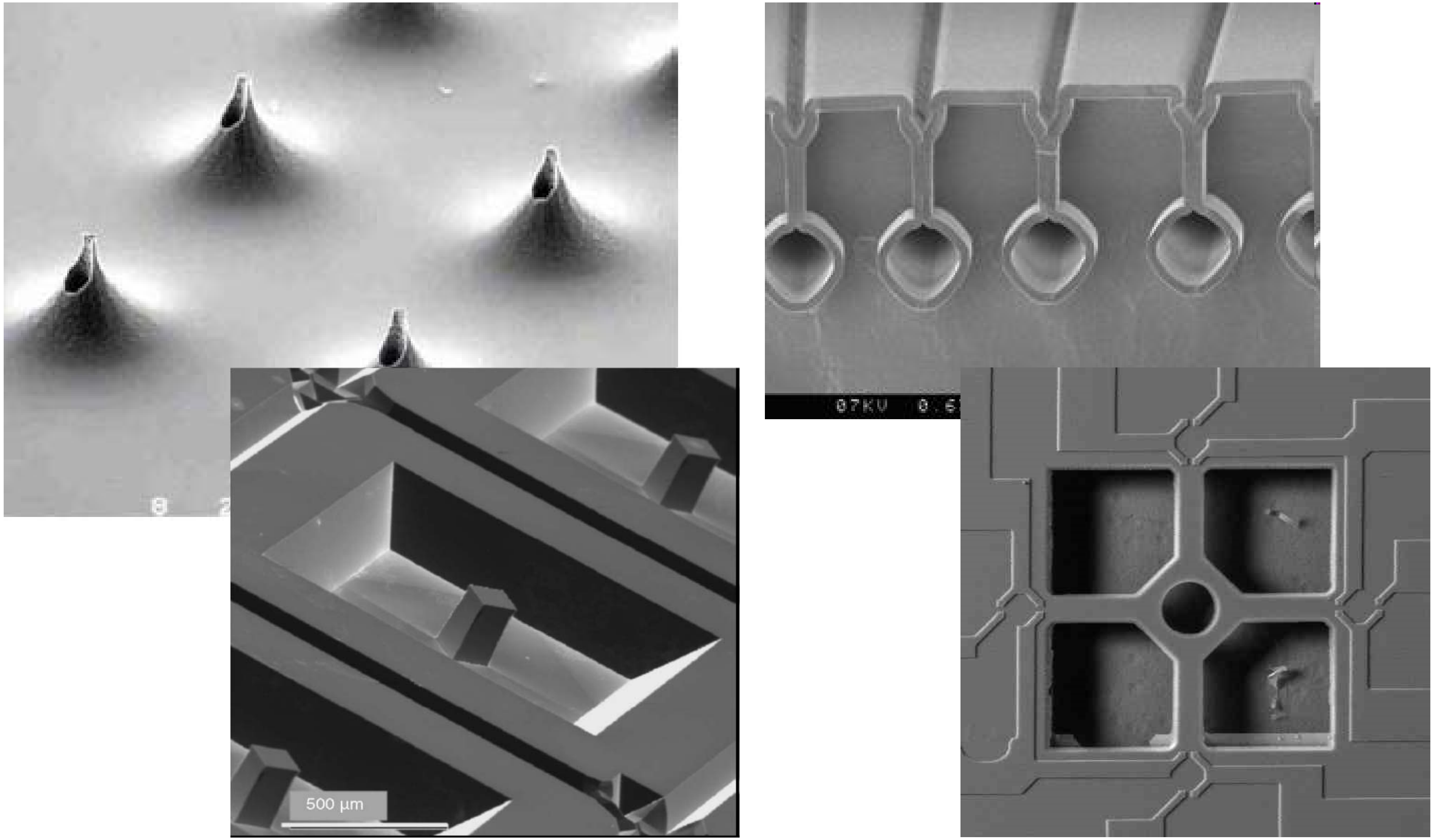
Solution:
inbuilt keeper
or perforated structures
or dry etching
or supercritical drying

EXAMPLES: SURFACE MICROMACHINING





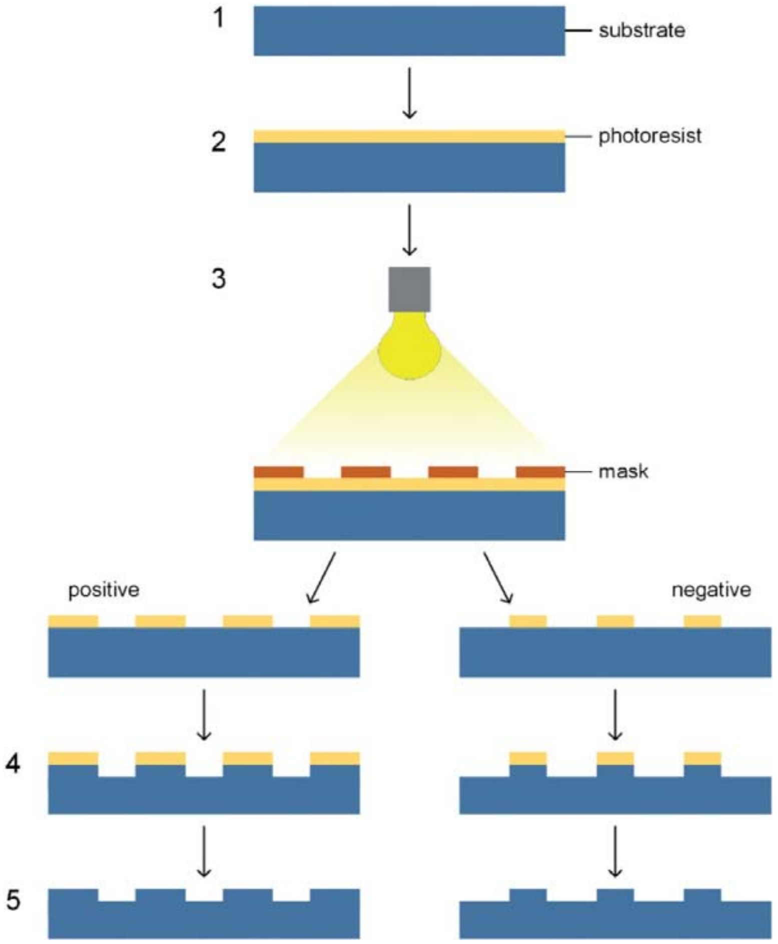
EXAMPLES: BULK MICROMACHINING



PHOTOLITOGRAPHY

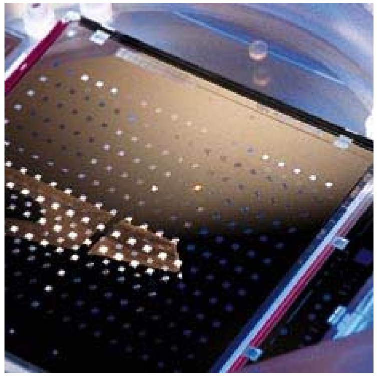
PHOTOLITHOGRAPHY PROCESS

SUBSTRACTIVE PHOTOLITHOGRAPHY



1. Surface treatments: cleaning, dehydratation
2. Photoresist spincoat / prebake
3. Exposure / development

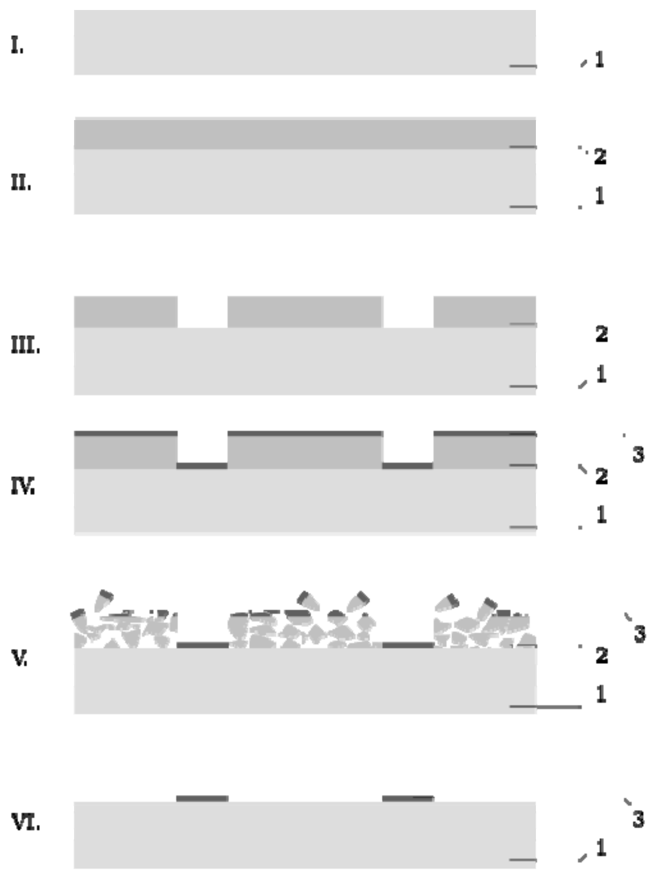
   Postexposure bake / softbake hardbake



4. Processing with photoresist masking
5. Photoresist removal, stripping, cleaning

PHOTOLITHOGRAPHY PROCESS – LIFT-OFF

ADDITIVE PHOTOLITHOGRAPHY

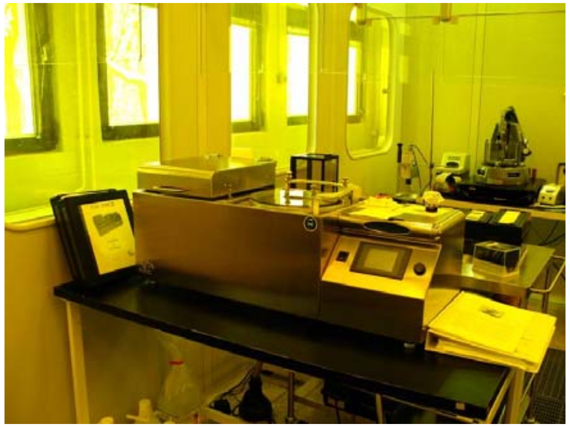


1. Surface treatments: cleaning, dehydratation
2. Photoresist spincoat / prebake
3. Exposure / development

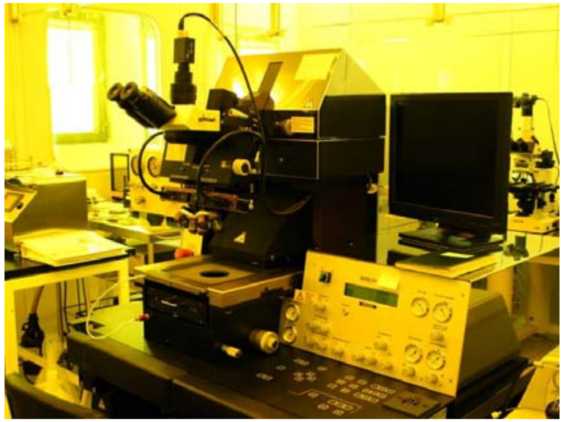
   Postexposure bake / softbake
4. Layer deposition
5. Photoresist removal, stripping, cleaning

PHOTOLITHOGRAPHY PROCESS

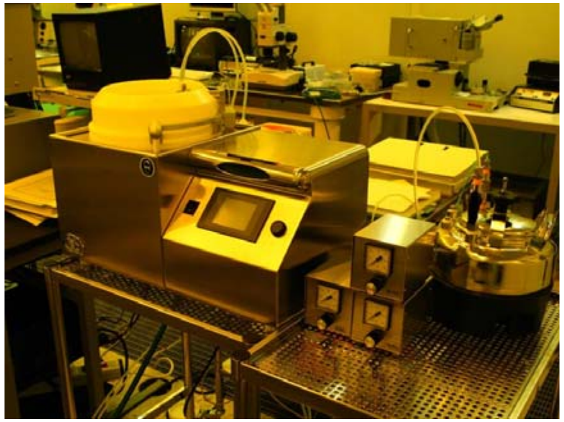
EQUIPMENTS - RADIATION



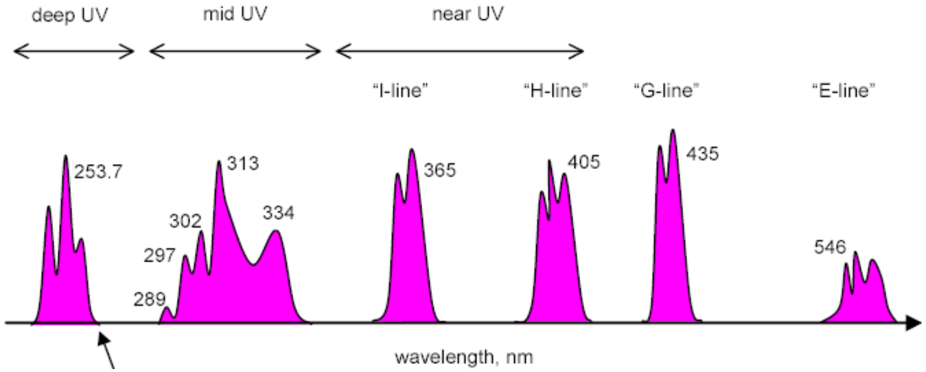
Spincoater – hotplate



mask alligner



developer



Hg lamp: 436 nm (g-line), 405 nm (h-line), 365 nm (i-line)

KrF laser: 248 nm / ArF lézer: 193 nm

Next generation: extreme UV (EUV): 13.5 nm

LAYER DEPOSITION

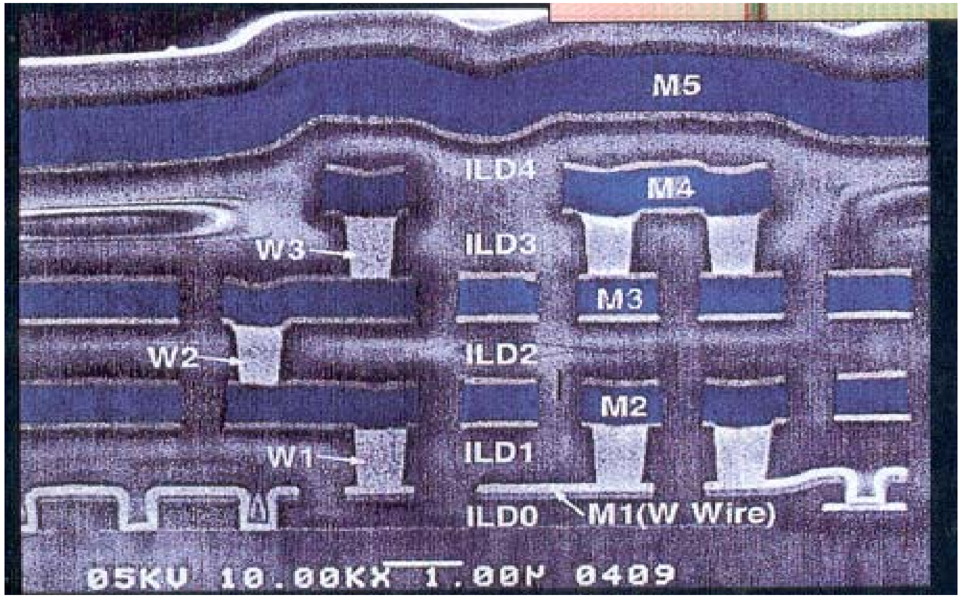
APPLICATIONS

- Microelectronics, semiconductor processing
- Micro-electromechanical systems (sensors, actuators, MEMS)
- Thermal conducting coatings (BeO, AlN, diamond)
- Photovoltaic devices (solar cells)
  - amorphous and microcrystalline Si layers on glass and polimer substrates
  - compound-semiconductors (CuInGaSe, CdTe)
  - single- and multicrystalline Si solar cells (HIT)
- Optical applications (filters, gratings, antireflexion layers, mirrors, etc.)
- Abrasion-resistant coatings
  - protection of optical devices (deposited diamond layers)
  - hard coating of tools (TiN, WC, B_4C, diamond, DLC)
  - coatings of human prosthesis
- Corrosion-resistant coatings
- Decoration coatings

STANDARD REQUIREMENTS

- homogeneous thickness on the substrate
- homogeneous composition
- homogeneous structure (amorphous, polycrystalline, epitaxal)
- homogeneous physical and chemical properties
- compactness (sponge vs. layer, pinholes)
- adequate adhesion
- low thermomechanical stress
- special requirements

  (friction, wettability, biocompatibility, etc..)
- economical
  - deposition rate
  - infrastructural maintenance
- step coverage



TECHNOLOGIES

Physical methods (PVD, Physical Vapour Deposition)

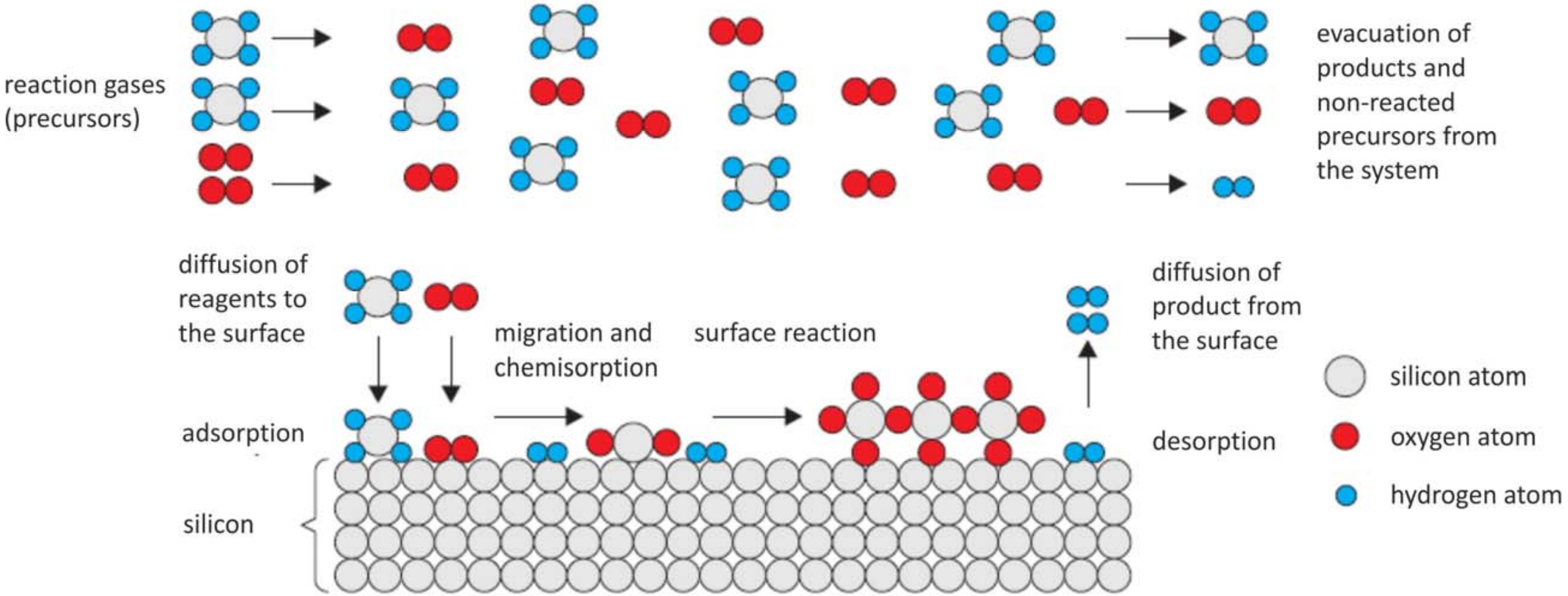
Solid source:	vacuum evaporation
	sputtering: DC, RF, magnetron
	MBE (Molecular Beam Epitaxy)
Melt source:	LPE (Liquid Phase Epitaxy)
	(single crystal growing, Czohralsky, Floating zone)

Chemical methods

Electrolite source:	plating
(solution, suspension)	setting, sol-gel technics)
gázfázisból:	**CVD (Chemical Vapour Deposition)**
	VPE (Vapour Phase Epitaxy)
	MOCVD (Metal Organic ….)
	LPCVD (Low pressure…)
	PECVD (Plasma enhanced…)
	MWCVD (MicroWave…)
	PACVD (Photon assisted…, or plasma assisted)
	ALCVD (Atomic Layer.. ALD(ep..), ALEpitaxy)

CVD – CHEMICAL VAPOUR DEPOSITION

- Chemical reaction of one or more gas phase reagents (precursors) on a solid substrate
- Surface catalysed reaction (not in the gas space)
- Solid product



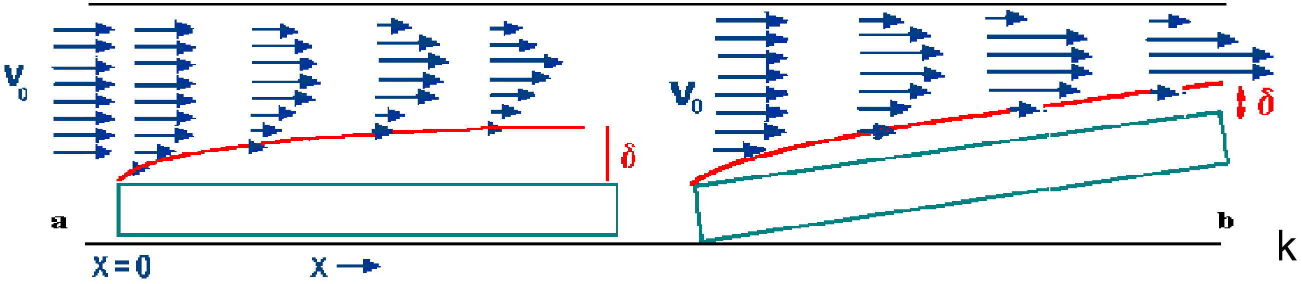
Atmospheric CVD - APCVD

- Small free path
- Reaction rate control: transport (reagent or product)
- Thermal activation

$\delta(x) = (\mu x/\rho v_o)^{1/2}$

μ kinematic viscosity

ρ density

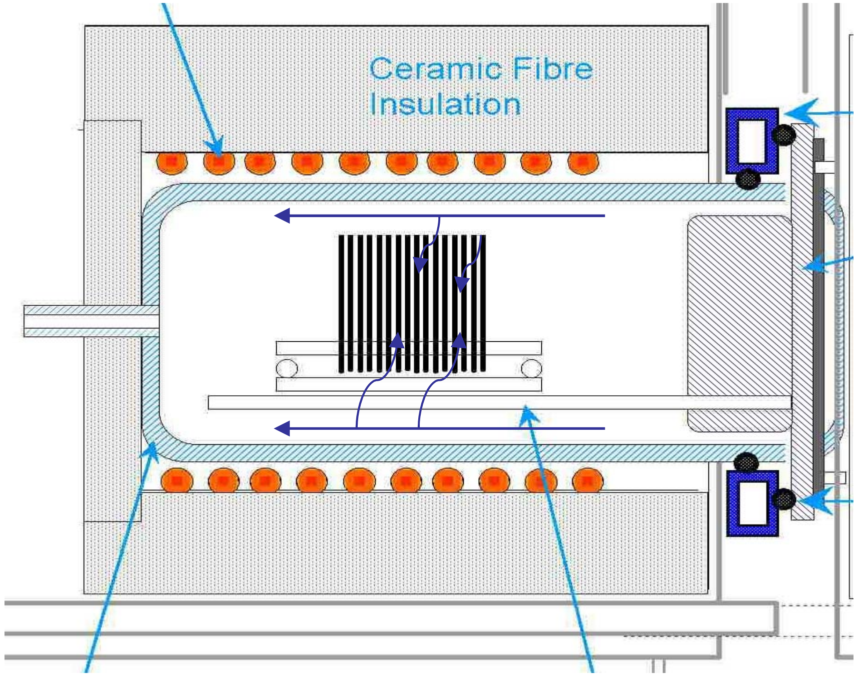


Thickness homogeneity ±10%, single wafer reactors

- SiO_2: silane + oxygen / 450oC

LOW PRESSURE CVD - LPCVD

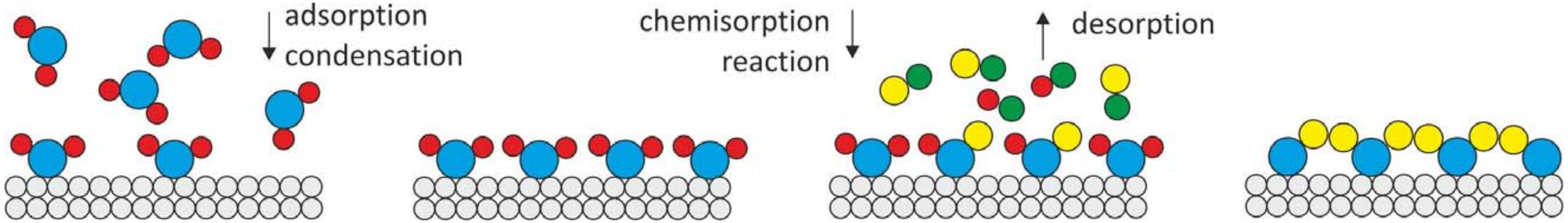
- Long free path
- Reaction rate control: chemical reaction
- Thermal / plasma activation



Thickness homogeneity ±2-6%, batch and single wafer reactors

ALD – ATOMIC LAYER DEPOSITION

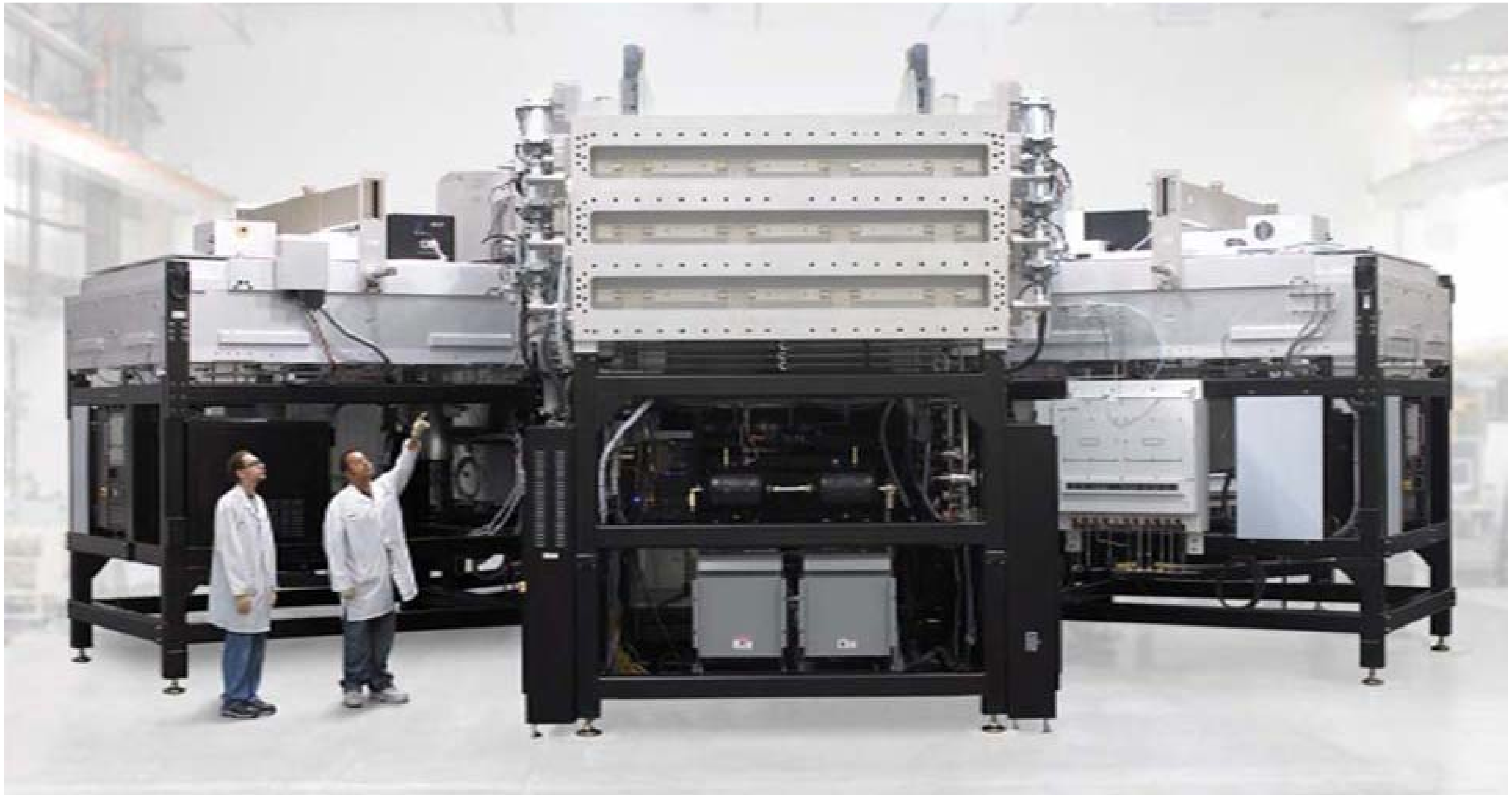
- Reaction rate control: chemisorption
- Thermal / plasma activation



- atomic / molecular precision
- excellent homogeneity
- excellent step coverage
- batch and single wafer reactors

Typical materials: Al_2O_3, ZnO, HfO, …

INDUSTRIAL SOLUTIONS



ETCHING

CHEMICAL ETCHING

Etching: removal of the solid material of the substrate by chemical reaction

Reagent: liquid or gas (or vapour, or plasma)

Wet etching:

- **Chemical** reaction on the liquid / solid interface – causing dissolution of solid material

Dry etching:

- Gas or vapour phase reagents at high temperature
- Gas phase reagent at **low temperature and pressure, active particles with extreme high reactivity, generated by RF induced plasma** discharge (free radicals or excited neutral particles) – isotropic etching
- **Physical etching** – non or moderate selective **sputtering** of the substrate atoms and molecules – directional / anisotropic etching

APPLICATIONS in IC TECHNOLOGY

Semiconductor wafer processing

- Elimination of mechanical defects by chemical polishing
- High quality surface development by chemical-mechanaical polishing

CMOS technology / micromachining

- Photoresist development
- Selective or total removal of oxides or nitrides
- Patterning of metal layers
- Selective or total removal of organic layers
- Contour etching: engineered undetcut profiles
- Anisotropic etching of si in MEMS structures
- Etching of polycristalline Si in MOS structures (poly-gate)

Analitical applications:

e.g. exploring foults (pinholes, crystalline foults

Packaging semiconductor devices: e.g. refreshing metal surfaces

WET CHEMICAL ETCHING

Requirements against the etching processes:

- uniform etch rate on the whole substrate surface
- high selectivity for the masking layer
  (for photoresist or other layer)
- high selectivity for substrate material
  (v_{layer} / $v_{substrate}$ >10..100)
- adequate etch rate corresponding to the thickness of the layer to be etched ($\approx$ 0,1-1 μm/min)
- possibly controlled by chemical reaction
  (not by transport)

WET ETCHING TECHNIQUES

Immersion etching

- High wafer number / economicalsti
- Rate control: temperature / stirring (bubbleing / stirring / ultrasonic tub)

Spray etching

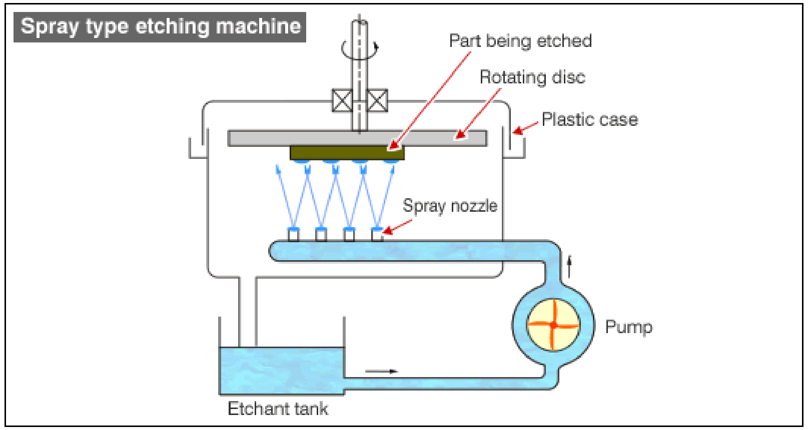
- Effective etch rate control (parameters: vaporisation drop size / pressure)
- Enhanced etch rate due to the continously fresh etchant
- Single wafer

Chemo-mechanical etching

- Wafer polishing (Si or polymers)

Electrochemical etching

- Selectivity and etch rate control (parameters: potential or current)



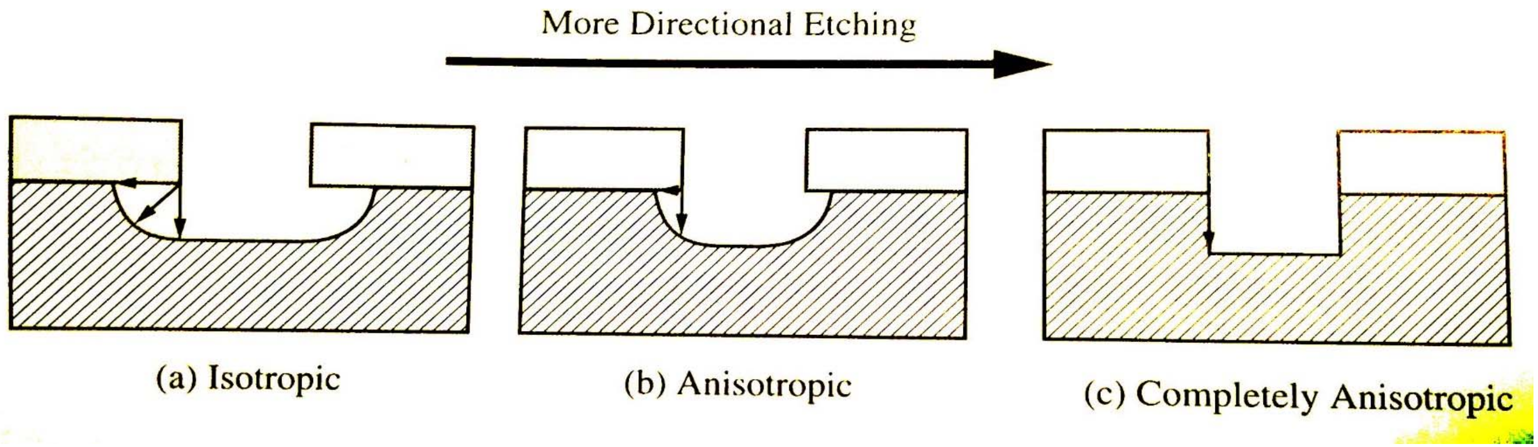
DIRECTION DEPENDENCY OF WET ETCHING

Isotropic etching: direction independent etch rate

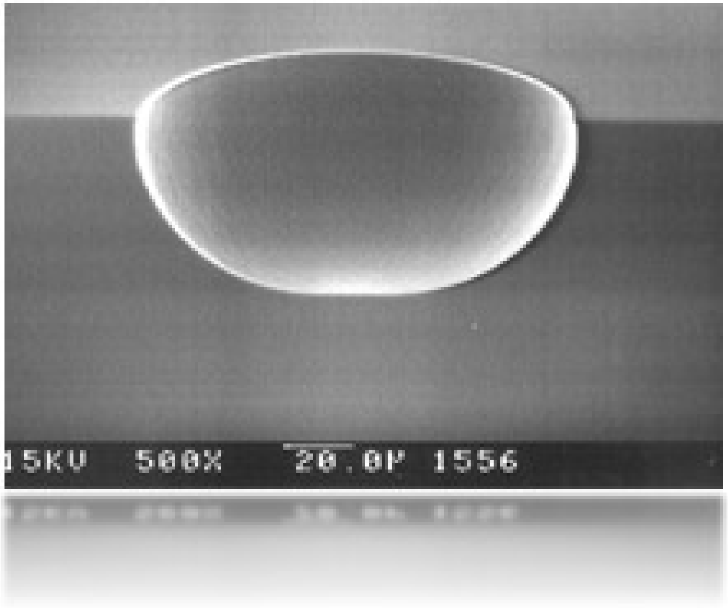
- Etching of amorphous and polycrystalline materials is typically isotropic
- Typically diffusion limited processes

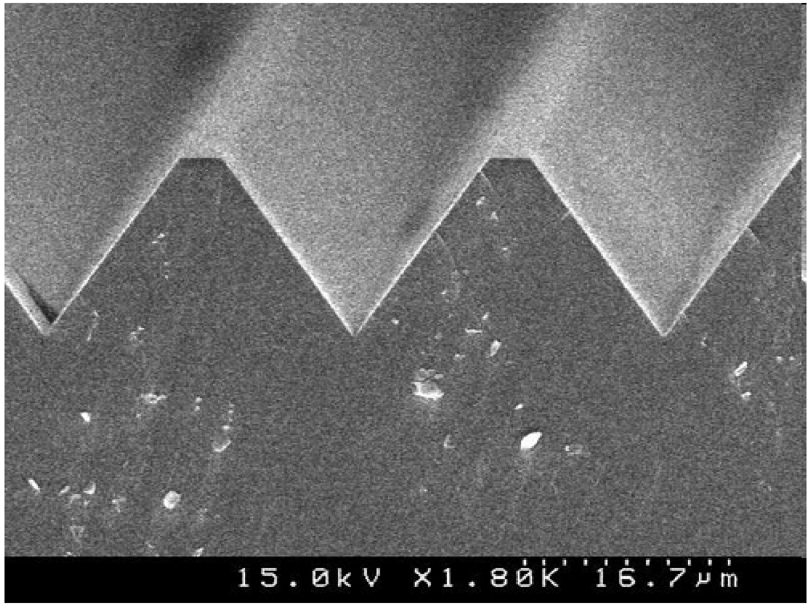
Anisotropic etching: direction dependent etch rate

- Etching of crystalline materials could be isotropic and anisotropic according to the composition of the etching solution and the reaction kinetics
- Typically reaction limited processes



ETCHING OF SILICON



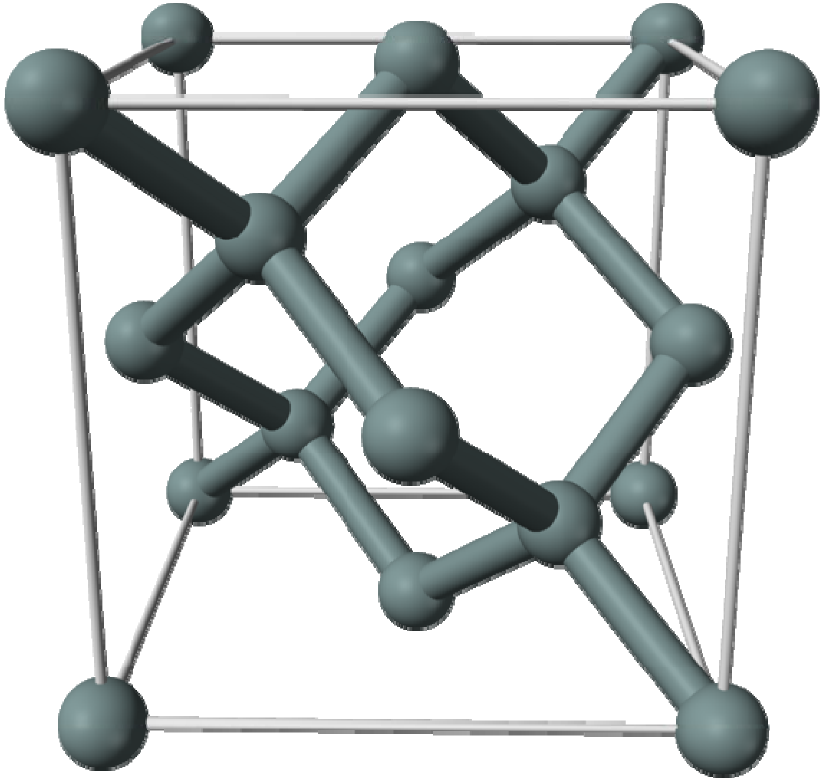


Isotropic:
uniform etch rate in each crystallic directions
(e.g. poly-Si etchant - HF-HNO_3-CH_3COOOH)

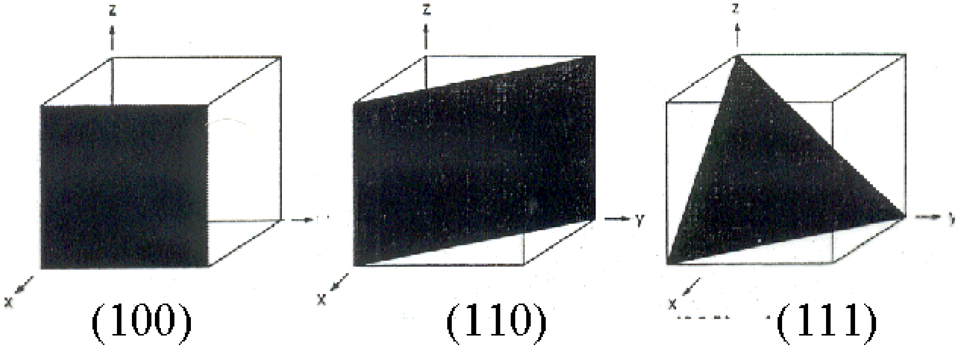
Anisotropic:
etch rates are altering according to the different crystallic directions
(e.g. alkaline etchants – KOH)

DIRECTION DEPENDENT ETCHING OF SI

Crystalline structure of silicon: face centered cubic



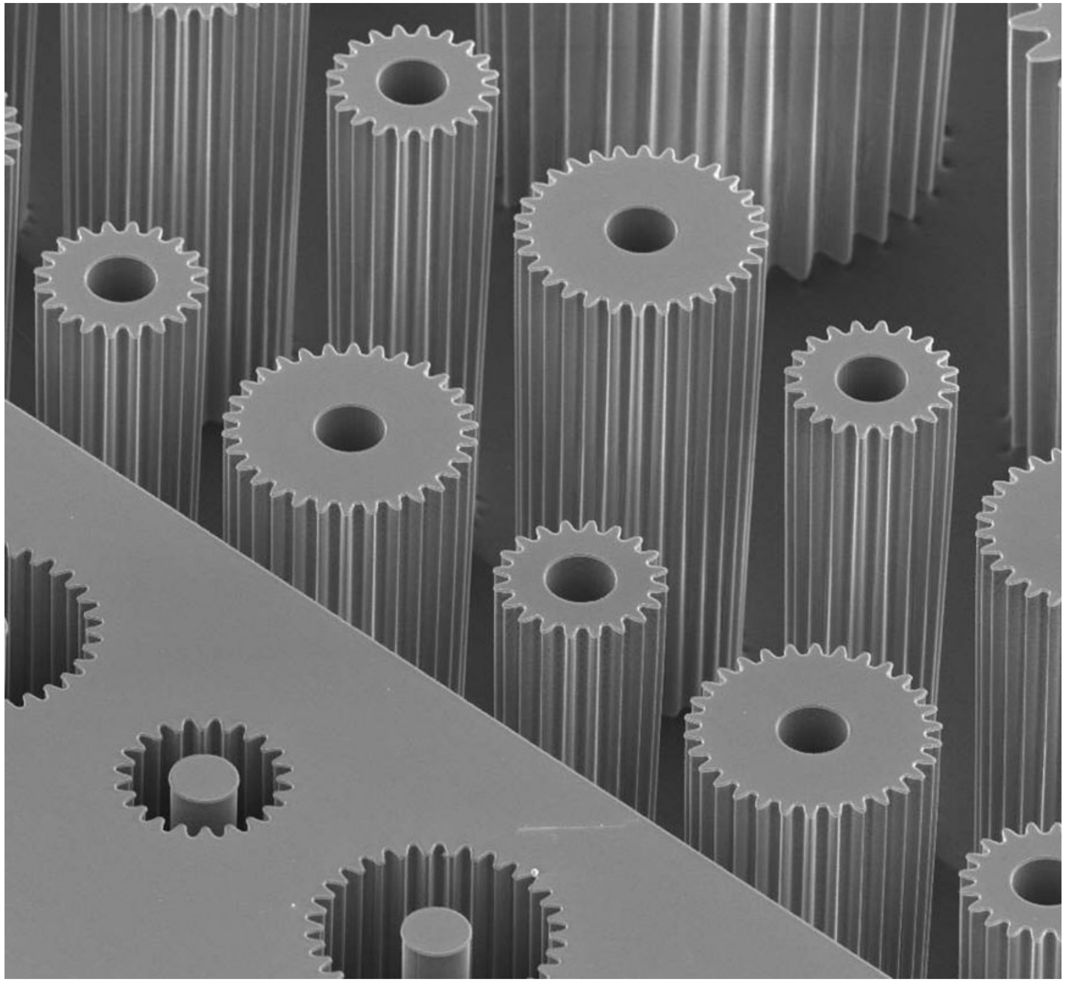
Typical crystalline planes:

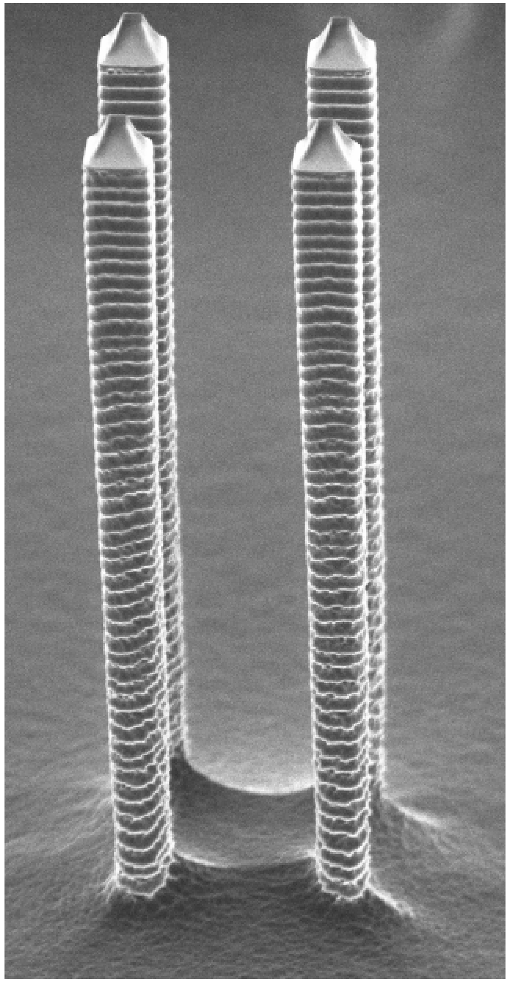


Si-Si bonding energies: $E_{\sigma(SiSi)(111)} >> E_{\sigma(SiSi)(100)} > E_{\sigma(SiSi)(110)}$

Etching rates: $v_{<111>} << v_{<100>} < v_{<331>}$

DRY ETCHING

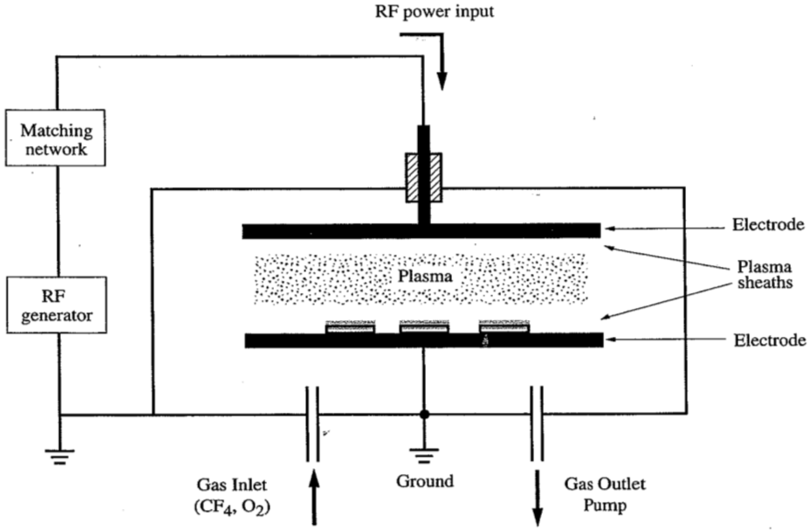


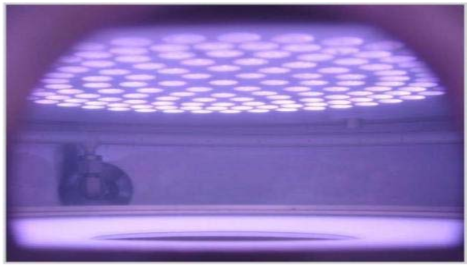


PLASMA ETCHING

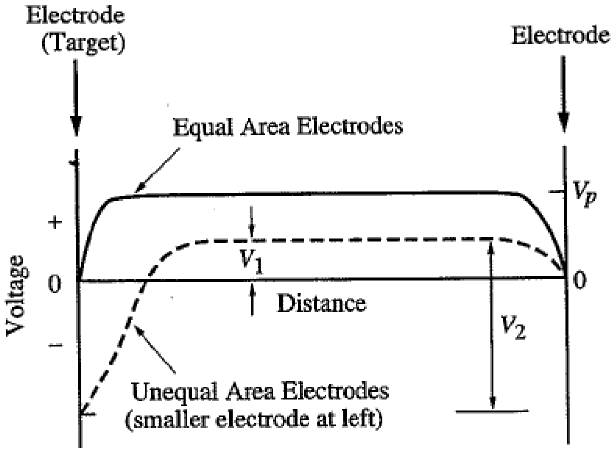
Plasma Glow

- Low gas pressure (1 mtorr-1 torr)
- High electric field on the electrodes, 13.56 MHz RF
- Ionisation of the gas atoms:
  e^- + ions





plasma glow – conducting gas
(ions, free radicals, electrons, natural particles),
Particles are excited by the quick electrons
and emit photons after relaxation.



DRY ETCHING PROCESSES

- Effective **chemical etching** by reactive radicals (atomic F)
- Directional / anisotropic **physical etching** by charged particles

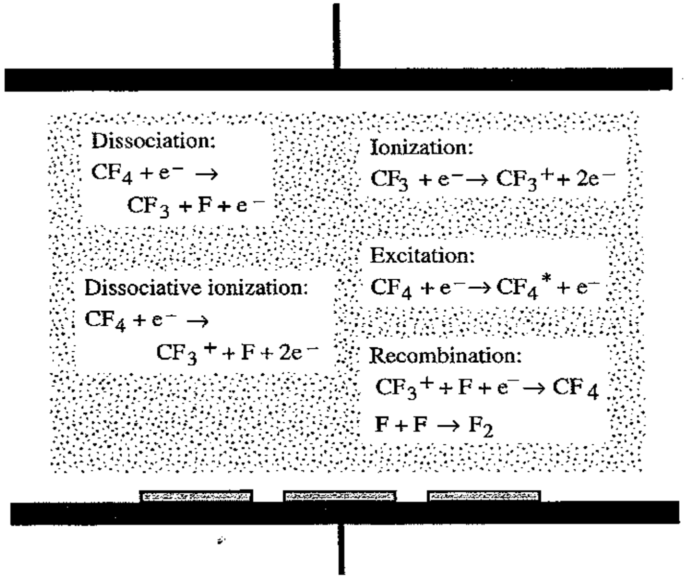


Figure 10–9 Typical reactions and species present in a plasma used for plasma etching.

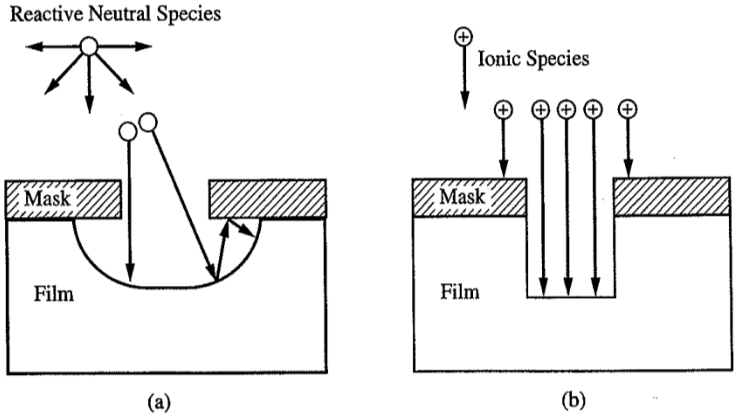


Figure 10–11 Fluxes of species in plasma etching: (a) fluxes of reactive neutral chemical species (such as free radicals), with a wide arrival angle distribution and low sticking coefficient; (b) fluxes of ionic species, with a narrow, vertical arrival angle distribution and high sticking coefficient (assumed equal to 1).

DRY CHEMICAL ETCHING

Free radicals (neutral, having non-bonding electron pair) – extremely reactive

$$CF_4 + e^- \rightarrow CF_3 + F + e^-$$
$$4F + Si \rightarrow SiF_4$$

Volatile products – must get away from the surface for continuous etching

Additive gases: possibly support the generation of reactive free radicals, enhancing etch rates!

e.g. ***O_2 gas*** *reacts with dissociated CF_3, CF_2 molecules, preventing the recombination to CF_4, enhancing the concentrtion of free F radicals*
BUT: O_2 dilutes the etchant gas!

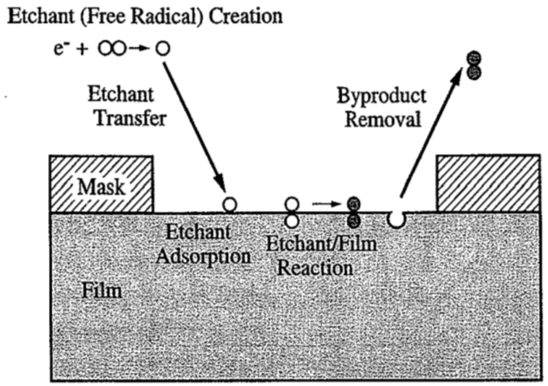


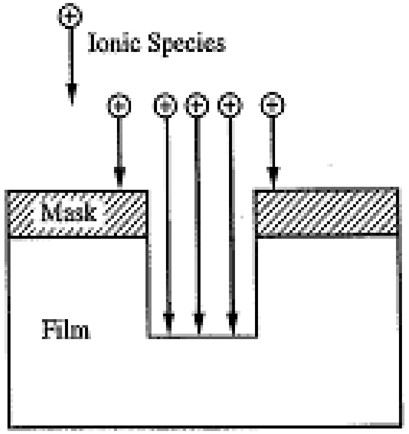
Figure 10–10 Processes involved in chemical etching during plasma etch process.

Isotropic etching:

1. Isotropic angular distribution of the incident velocity vector (particles)
2. Low surface adhesion / sticking coefficient (long path till reaction

HIGH SELECTIVITY

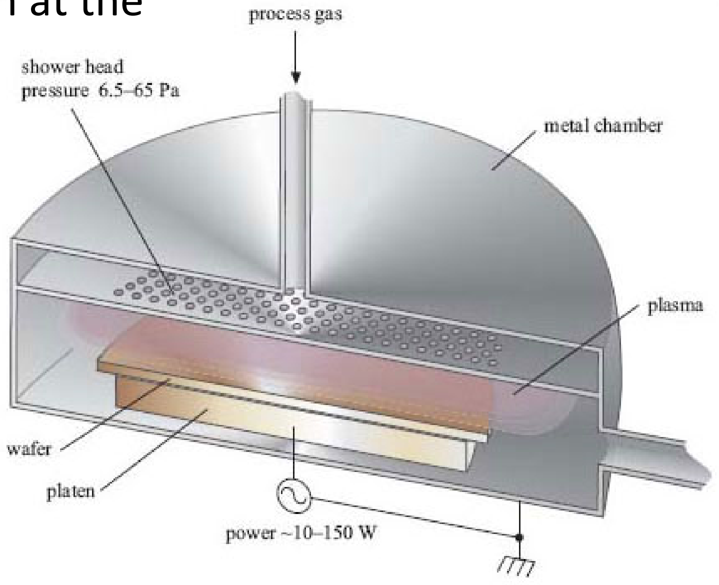
DRY PHYSICAL ETCHING



- **Positive ions are accelerating towards the electrodes** due to V_p (one is the substrate holder)
- Anisotropic etching:
  - Direction dependent etching rate of the incident ions due to the directional electric field
  - High adhesion / sticking coefficient – reaction at the moment of incidence
- **LOW SELECTIVITY**

Technologies:

- Sputtering or ion etching
- Focused Ion Beam etching (FIB)
- Magnetically localised ion etching



ION-ASSISTED ETCHING

Chemical-physical dry etching

(combination of the two processes)

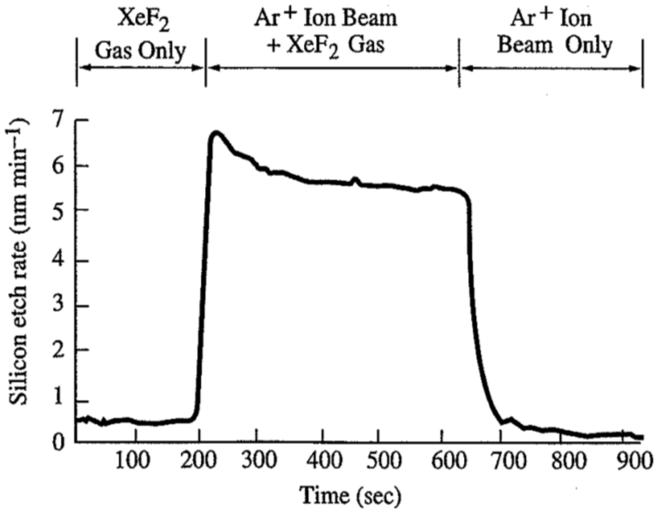
Ions + natural free radicals etch dependently:

- Can increase **selectivity and orientation dependent reaction rate**
- The etch rate is not the sum (higher)
- The etch profile is not a linear combinatin, but similar to physical etching (vertical etch rate increases)

The ion bombardment enhances one of the component of the chemical etching (surface adsorption, etching reaction, generation / removal of the product) anisotropic way

Technics:

- Reactive ion etching, sputtering
- Reactive ion beam etching
- Chemical enhanced ionbeam etching



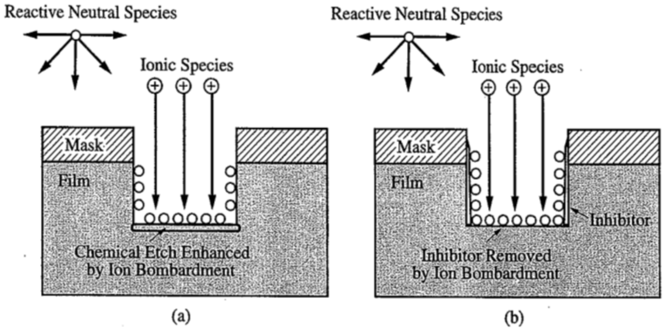


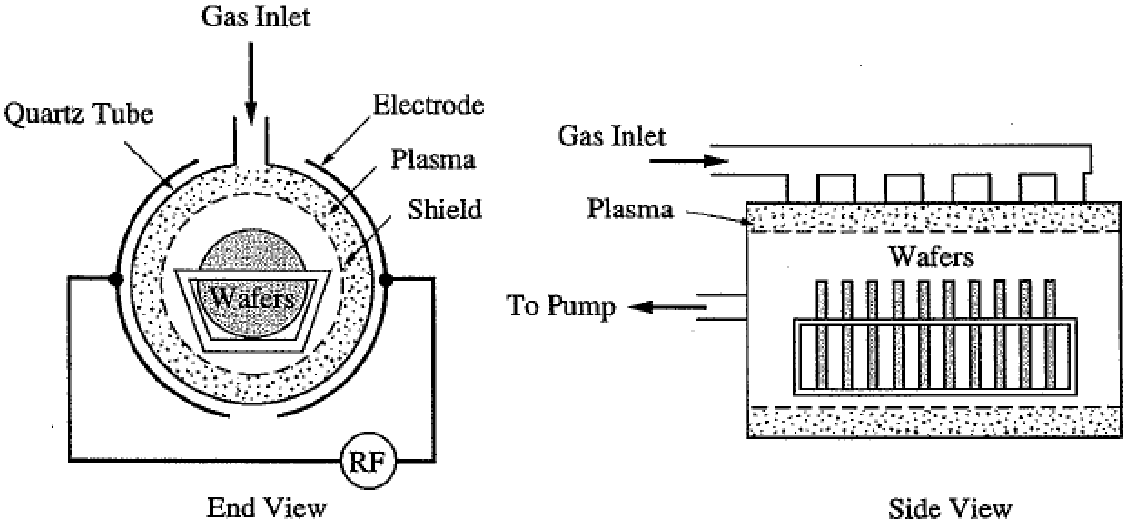
Figure 10–13 Illustration of ion-enhanced etching. In (a) the chemical etch reaction is enhanced by ion bombardment. In (b) an inhibitor is formed which is removed by ion bombardment, allowing chemical etching to proceed. In both cases, anisotropic etching results.

PLASMA ETCHING EQUIPMENTS I.

Cylindrical / barrel type plasma etcher

- Wafer in holder (not on the electrode), multiwafer process
- Isotropic chemical etching, high selectivity, low fault generation
- Inhomogeneous etch rate on the wafer
- p=10-1000mtor

For not critical etching steps
resist removal
in O_2 (ashing)



PLASMA ETCHING EQUIPMENTS II.

Planar type plasma etcher - Plasma mode

- The wafer is on the (bigger) grounded electrode facing to the oposite electrode – higher homogeneity, mainly chemical, adequate selectivity, slight anisotropy
- Weak ion bombardment , potential difference 10-100V
- The smaller electrode is sputtered
- p=10-500mtorr
- Ion concentration ~ 10^{9}-10^{10}cm^{-3}

For not critical etching steps
resist removal in O_2 (ashing)
Isotropic silicon-nitride etching

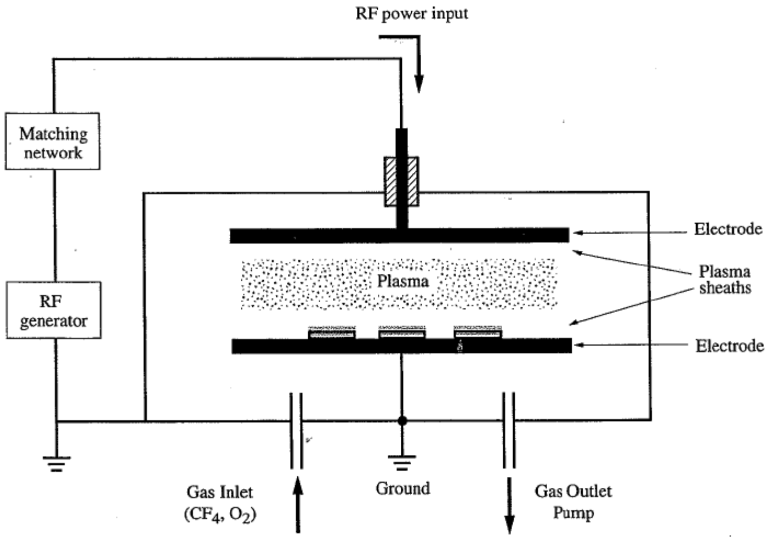


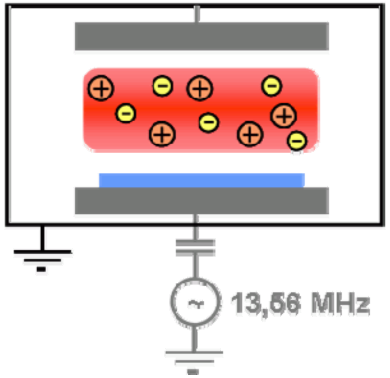
Figure 10–7 Schematic diagram of an RF-powered plasma etch system.

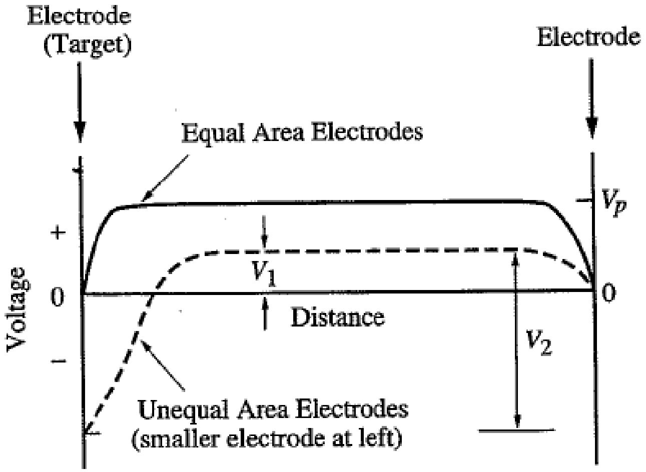
PLASMA ETCHING EQUIPMENTS III.

Planar type plasma etcher – RIE (Reactive Ion Etching) mode

- The wafer is on the smaller electrode – single wafer process
- The bigger electrode is grounded and connected to the chamber wall, higher potential difference in the range of 100-800V (bias) - ion enhanced / assisted anisotropic etching
- More directional etch in case of low pressure, but lower plasma density (10-100 mtorr), ion concentration ~ 10^9-10^{10} cm^{-3}
- Moderate etching rate 100 nm/min
- Lattice faults, charging, trenching

Examples:
SiO_2: CHF_3
poly-Si, Si_3N_4: SF_6+ O_2, NF_3
Al: Cl_2, BCl_3





PLASMA ETCHING EQUIPMENTS IV.
HDPE - High Density Plasma Etching

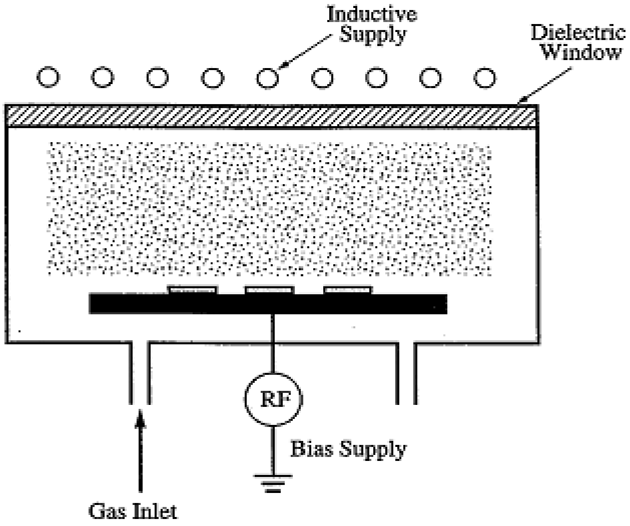


Figure 10-16 Schematic diagram of High-Density Plasma (HDP) etch system. This configuration is powered by an Inductively Coupled Plasma (ICP) source which produces and controls the high-density plasma. The RF wafer bias independently controls the ion energy.

- **Independent plasma density** and **ion energy**
- ECR (electron-cyclotron-resonance) or ICP (inductively coupled plasma) source generates 10^{11}-10^{12} ion/cm^3 plasma density, without high sheath bias – lower pressure can be applied 1-10 mTorr – highly directional (less collision in the sheath)
- RF source developes the potential difference, defines the bombarding ion energy, (can be decreased besides high ion density – decreased substrate deterioration
- high etch rate: some μm/min

Similar effect as in case of ion enhanced etching!

DRIE INTRO

DRIE – Deep Reactive Ion Etching

Etching depth / trench width > 10:1 (MEMS, DRAM capacitors)

Doubled power sources:

- ICP to achieve extremely high density reactive radicals + ions
- CCP DC self-bias for definition ion energies

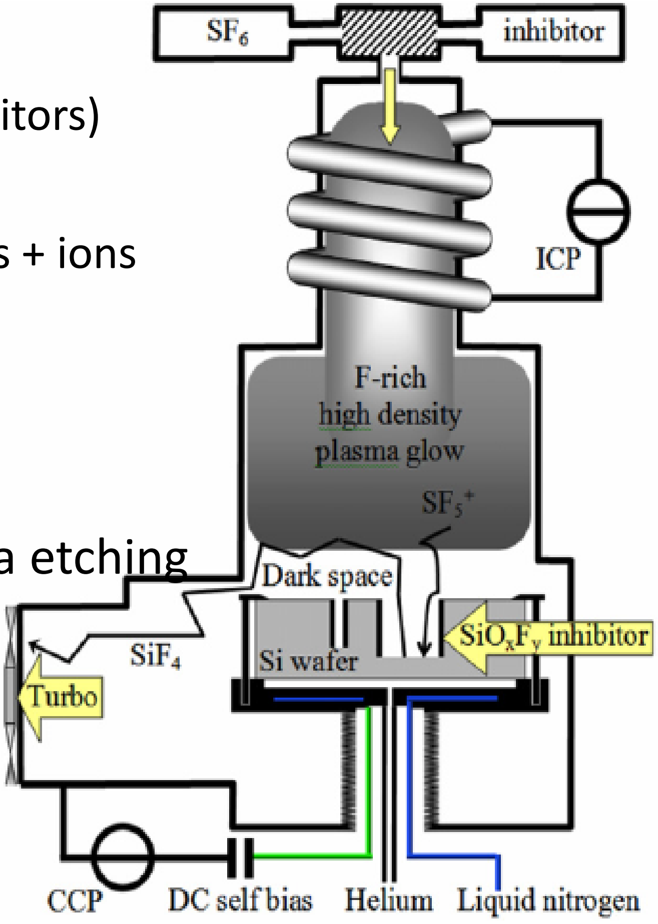


Figure 1. A dual source DRIE system.

Si DRIE

Gas composition: halogen based accelerated plasma etching

- F-based, (e.g. SF_6) quick isotropic etching
- Cl-, Br-based (e.g. Cl_2, HBr) anisotropic with ion assisted etching, but slower and poisoning

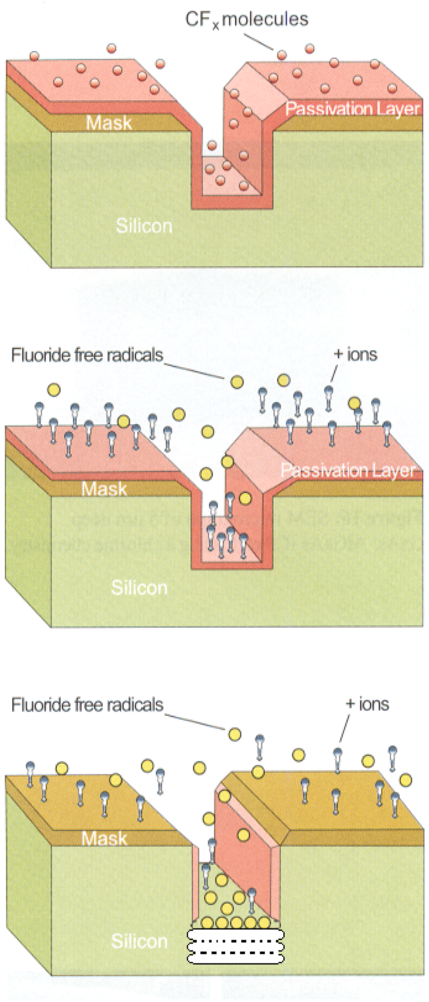
Mixed mode DRIE / Cryo

$SF_6 + O_2$ @ cryo °C

Pulsed mode DRIE / Bosch

$SF_6 + C_4F_8$ @ RT

DRIE – BOSCH PROCESS



- Passivation
  $C_4F_8 \rightarrow n\ CF_2$ (PTFE)

- Etching
  $SF_6 \rightarrow F$ + ions
  ion bombardment + polymer etching
  (excluding the vertical walls)

- SF_6 isotropic or
  slightly anisotropic Si etching

DRY ETCHING

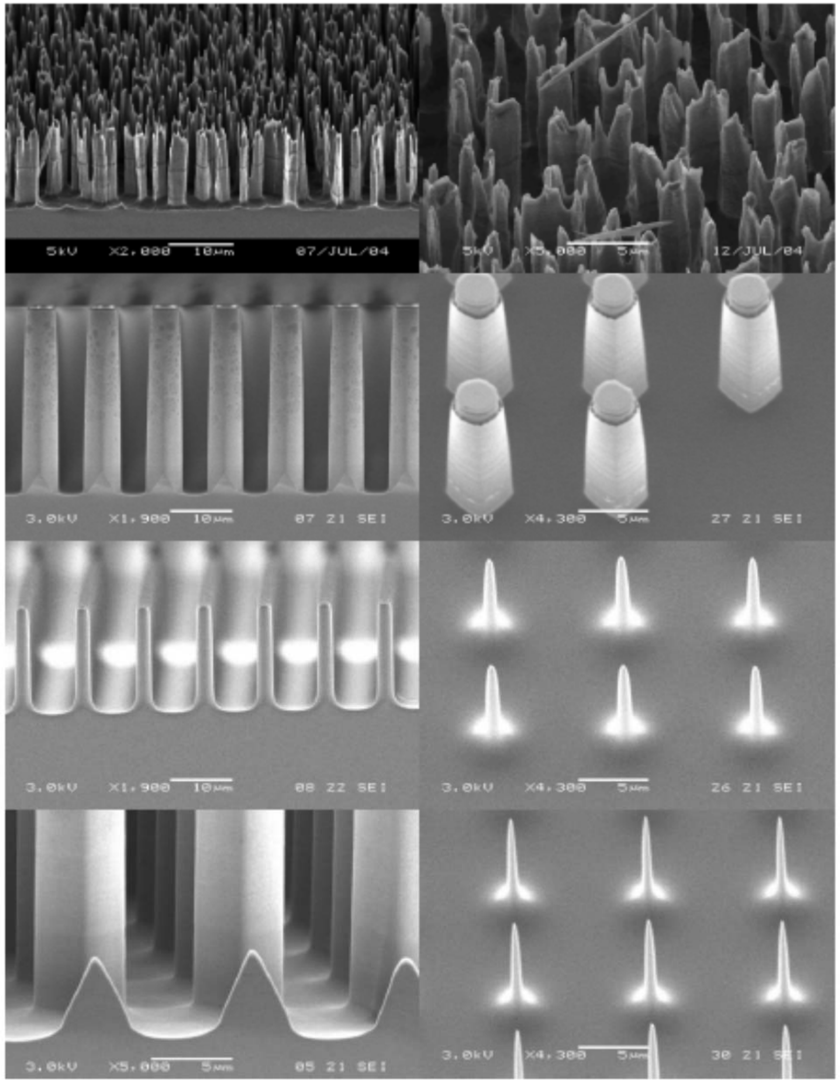


Figure 19. (Top) Black silicon and (rest) optimized result for cryogenic temperature mixed-mode DRIE (see figure 27).

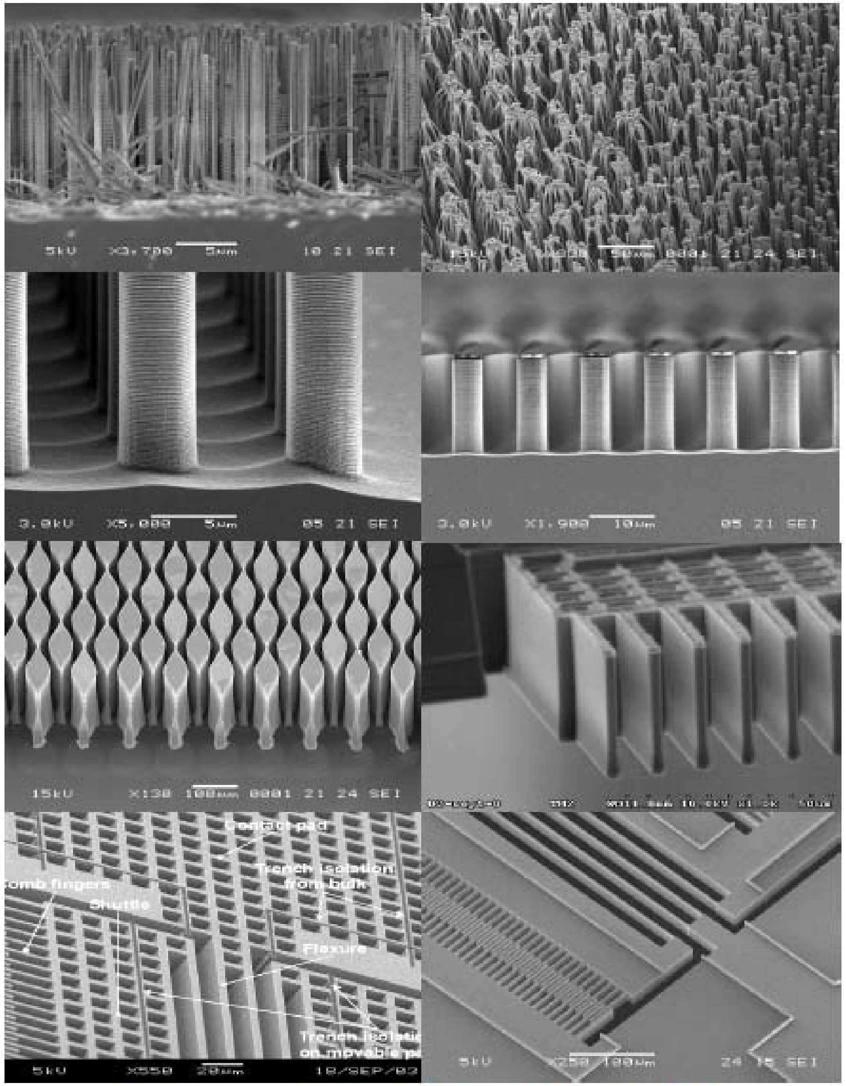


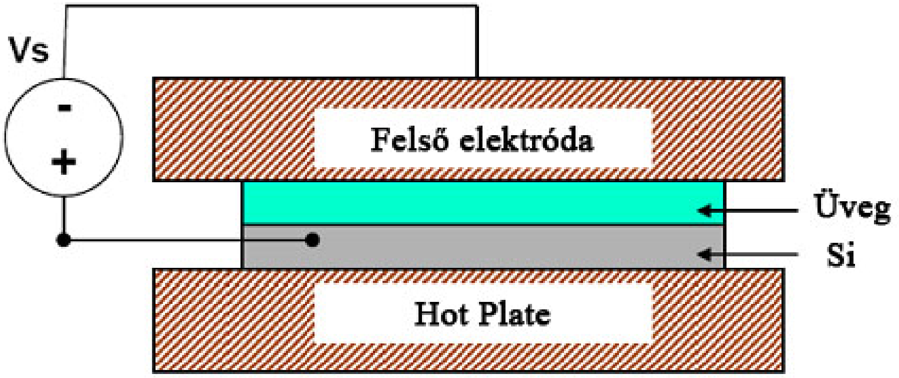
Figure 27. Typical result for room temperature pulsed-mode DRIE (see figure 19).

WAFER BONDING

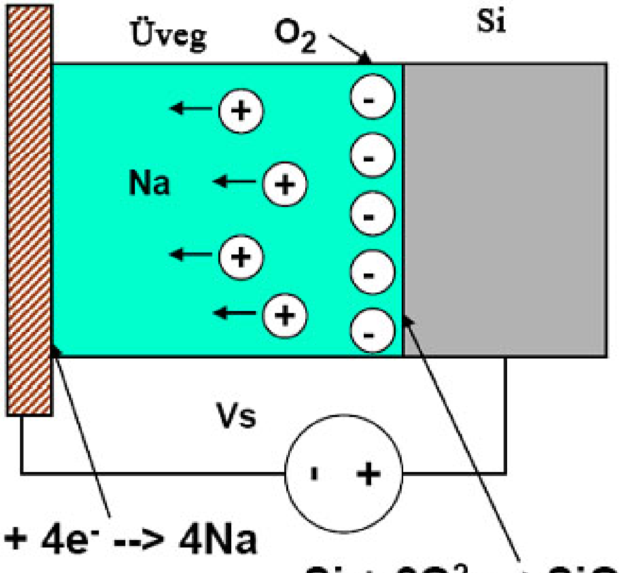
ANODIC BONDING

- Si + Special glass (high alcaline-ion concentration)
- Moving Na⁺ ions – depleted space-charge layer
- Covalent bonding of silicon and oxygen

- Low sensitivity for surface roughness



200°C<T<450°C
200V<Vs<2000V



$4Na^+ + 4e^- \dashrightarrow 4Na$

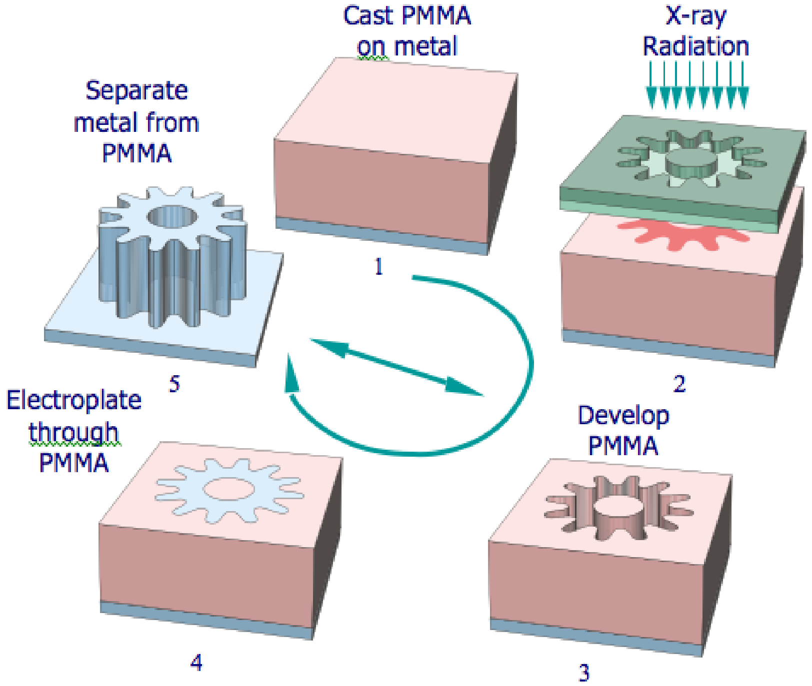
$Si + 2O^{2-} \dashrightarrow SiO_2 + 4Na$

LIGA

LIGA (KIT)

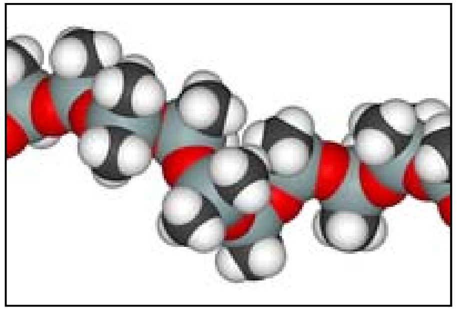
Lithographie, Galvanoformung, Abformung (Lithography, Electroplating, Casting)

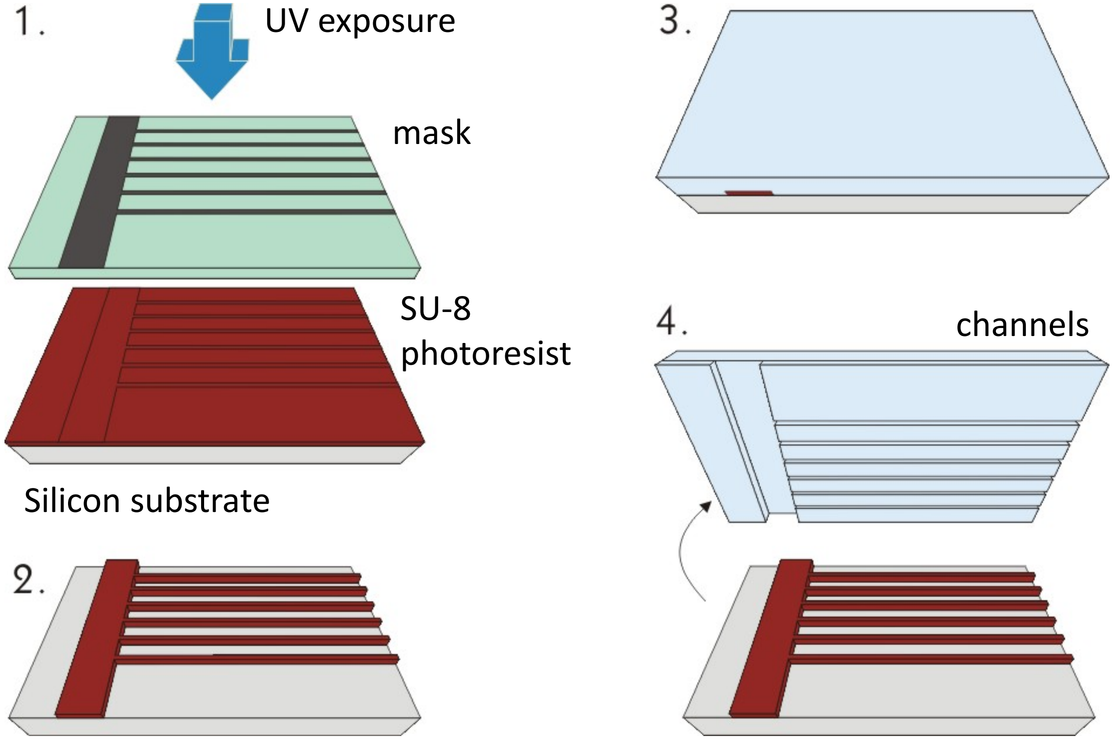
- Fabrication microstructures with high aspect ratio (100:1)
- Vertical sidewalls, 10nm surface roughness (optical structures)
- Height: from 10μm to some mm
- X-ray LIGA (PMMA) / UV LIGA (SU-8)



SOFT LITHOGRAPHY

FABRICATION PDMS POLYMER MICROFLUIDIC STRUCTURES





Advantages:

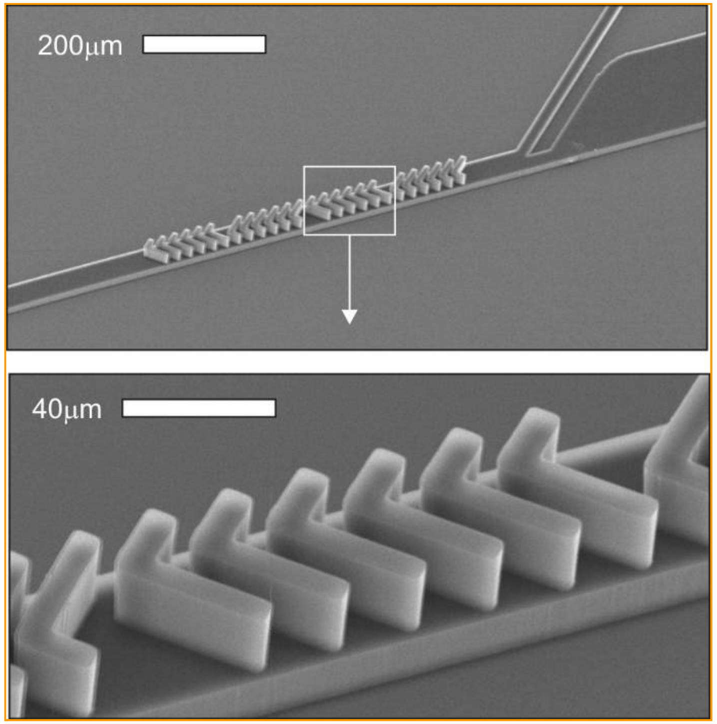
- biocompatibility, flexibility, transparency
- cheap, fast, easy to use
- covalent bonding to Si, glass and PDMS surfaces

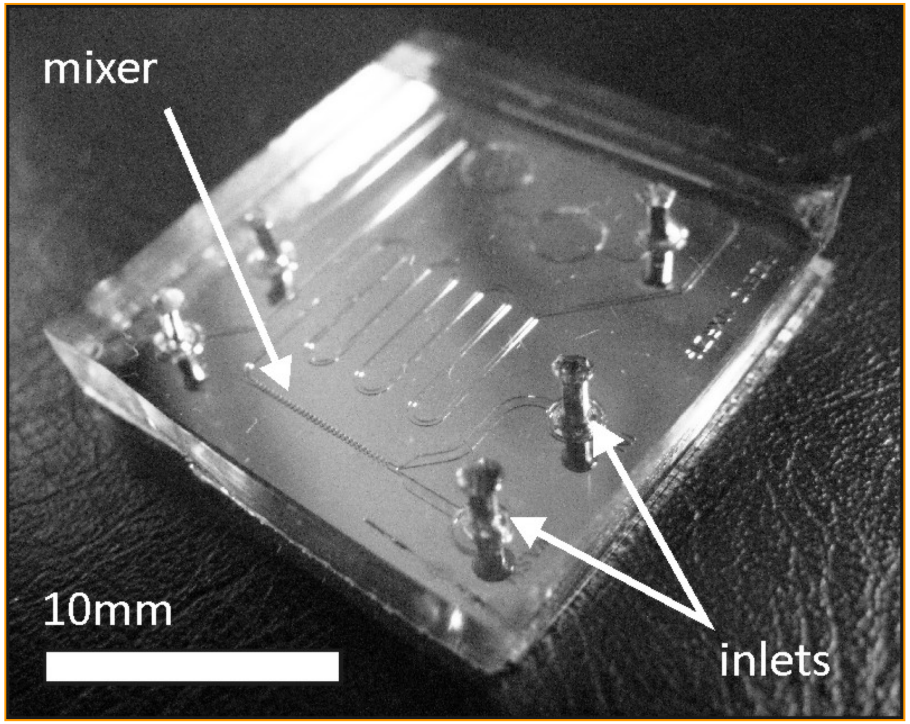
Disdvantages:

- hydrophobic
- non-specific molecule (e.g. protein) adsorption

FABRICATION PDMS POLYMER MICROFLUIDIC STRUCTURES

- Multi-layered 3D SU-8 technology for structuring moulding master
- FAST PROTOTYPING – PDMS moulding / casting

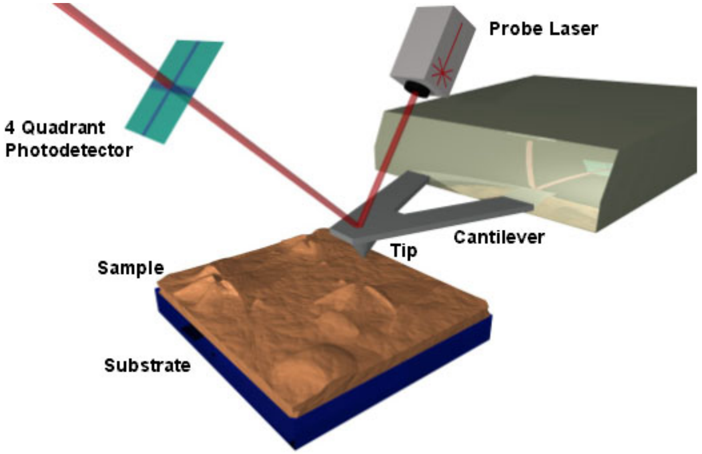


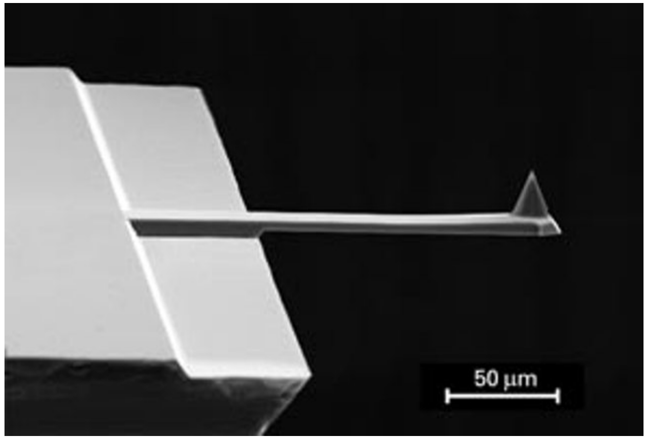


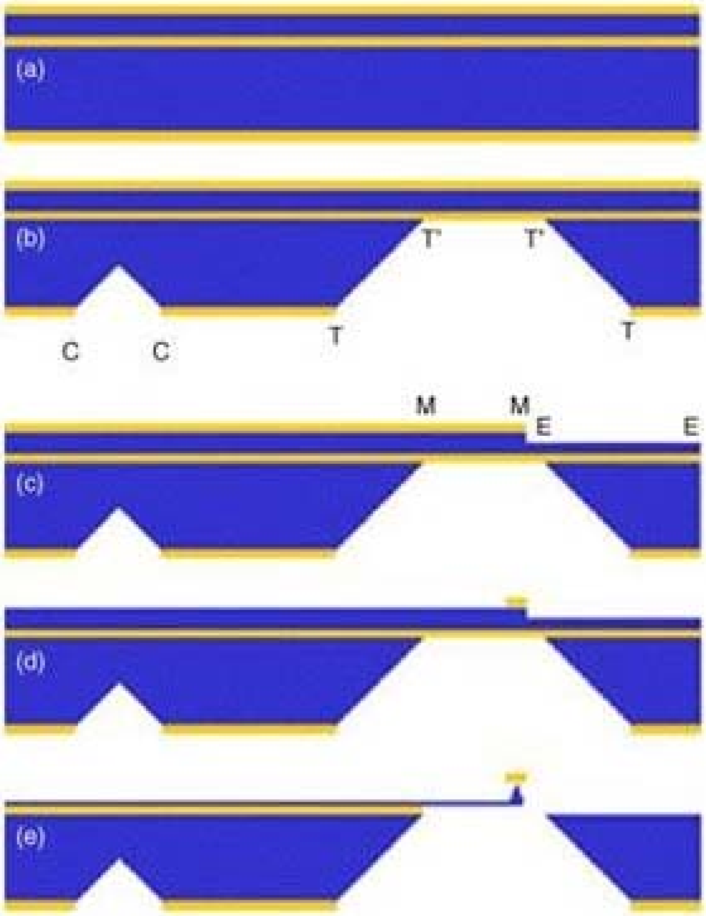
Hering-bone type chaotic mixer

EXAMPLE DEVICES

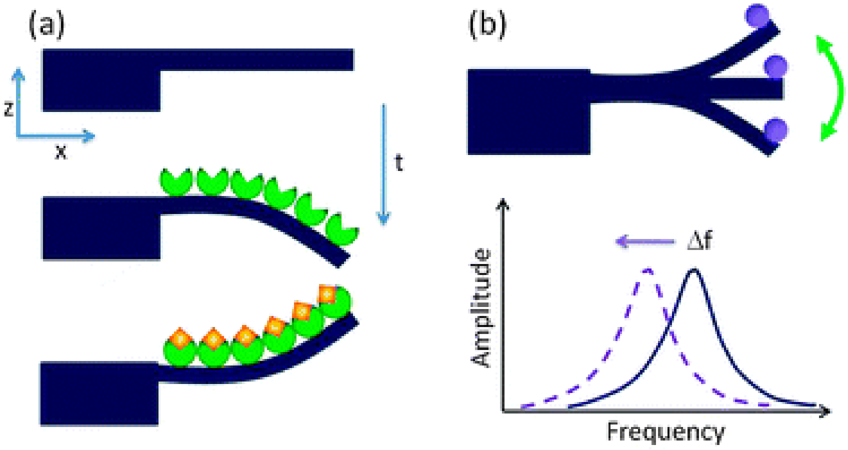
CANTILEVER – BULK MICROMACHINING

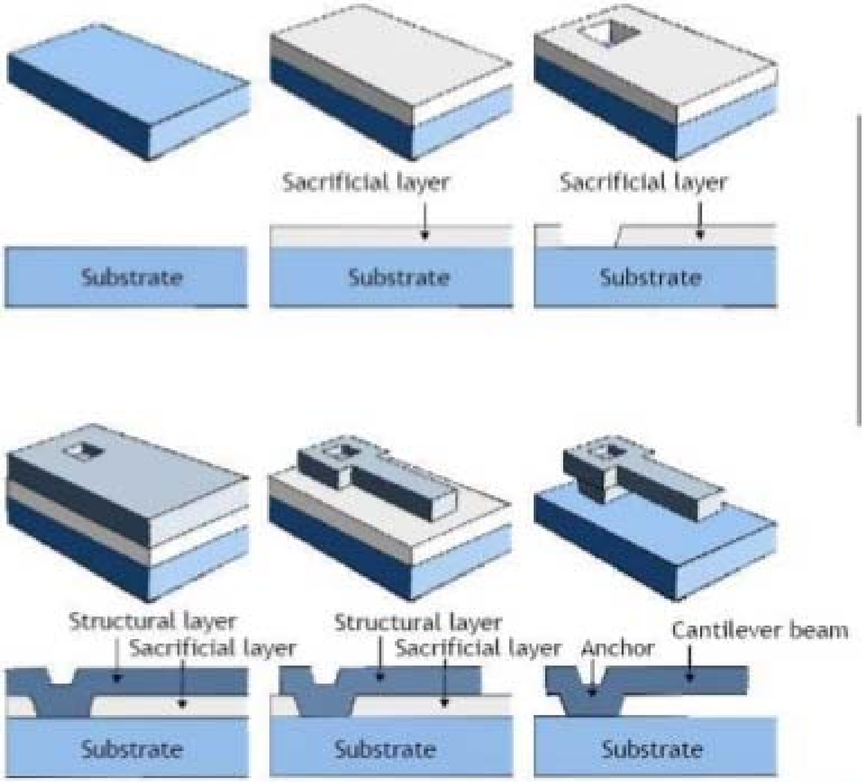


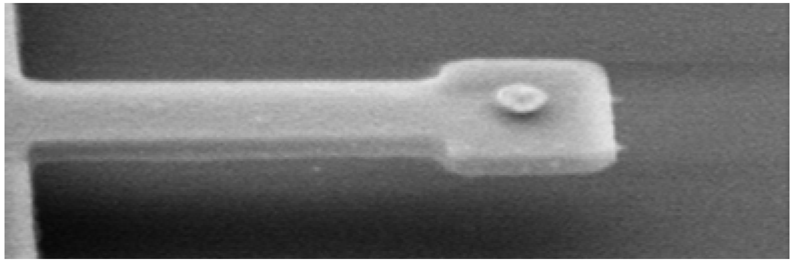




CANTILEVER – SURFACE MICROMACHINING



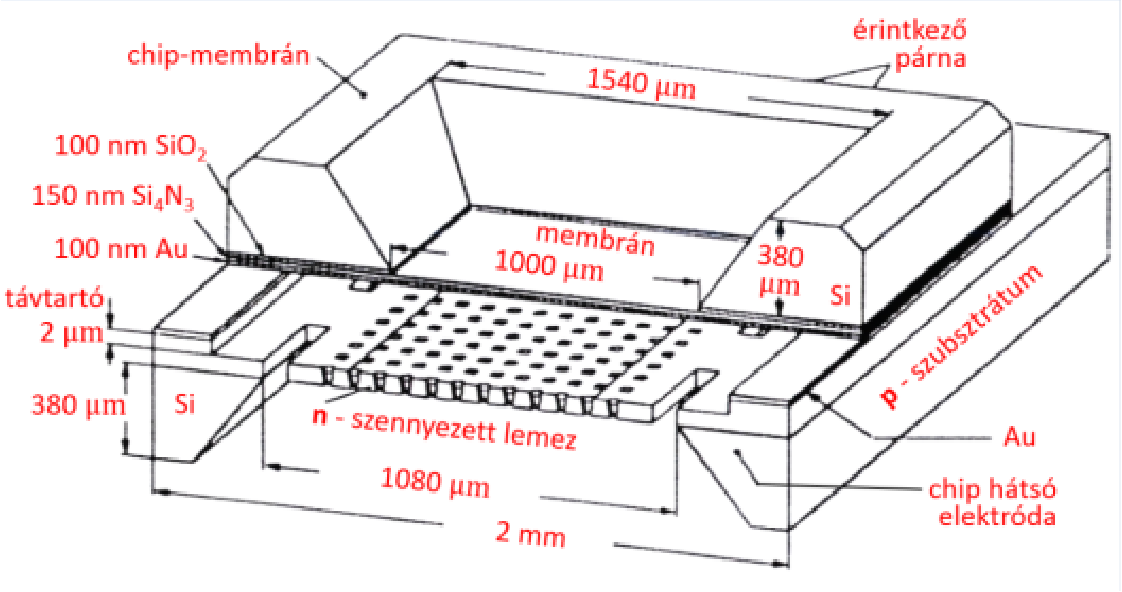


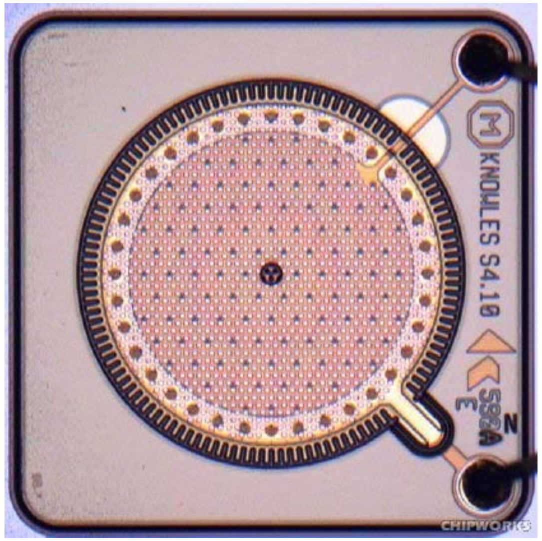


EXAMPLE DEVICES

MICROPHONE

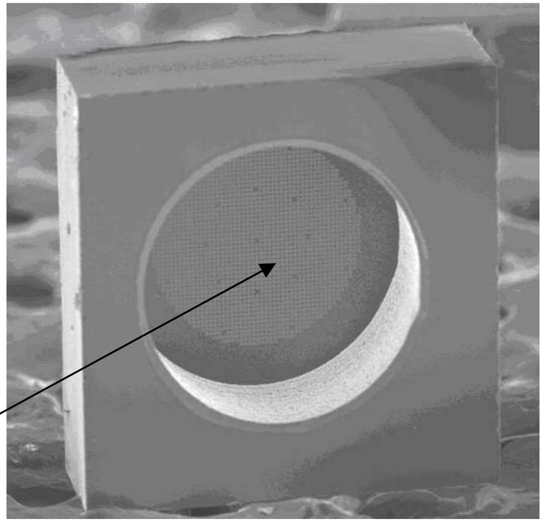
High Performance MEMS microphones (3-4 pcs / phone)





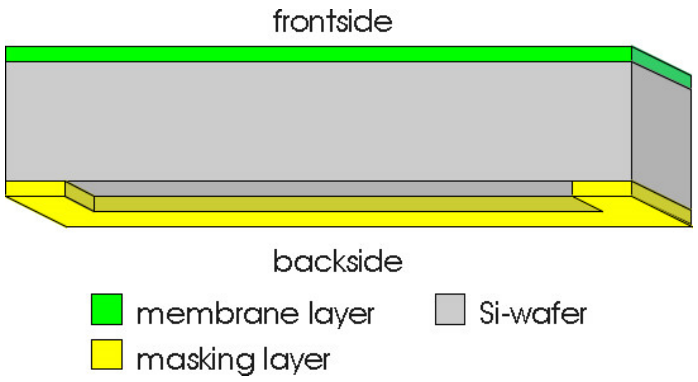
Top electrode: Au SiO_2 / SiN_x membrane
Bottom-electrode: n-Si

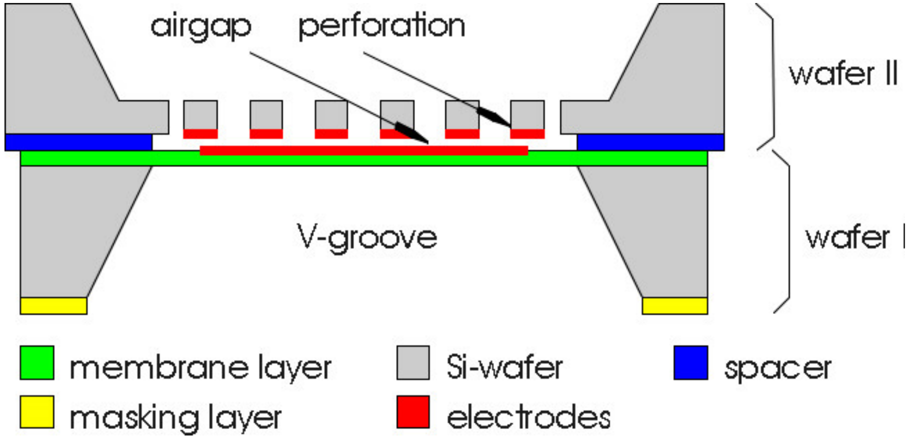
$$C_o = \varepsilon \frac{A}{d} \qquad \frac{\Delta C}{\Delta d} = -\varepsilon \frac{A}{d^2}$$

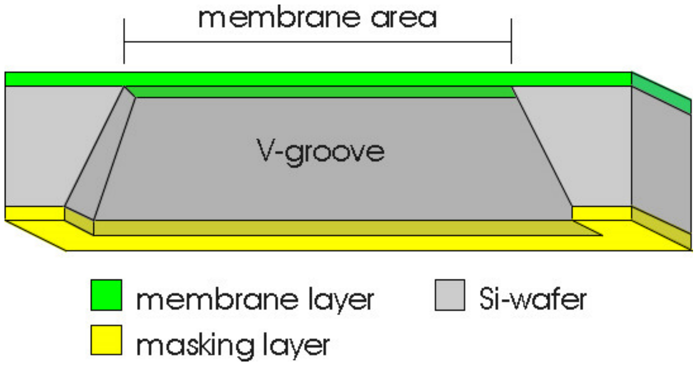


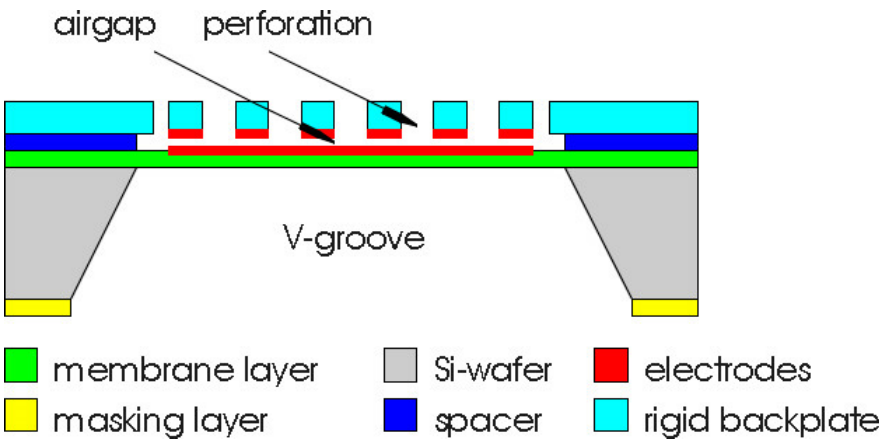
DRIE (deep reactive ion-etching) etched membrane

MICROPHONE – BULK MICROMACHINING (KOH)

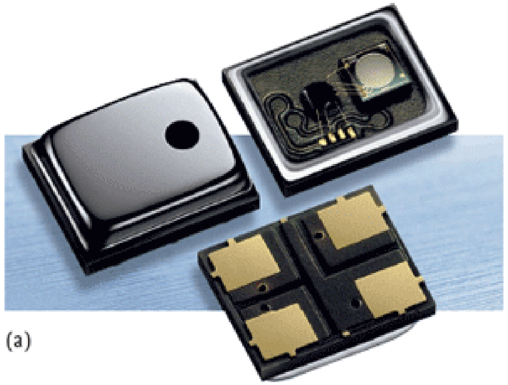


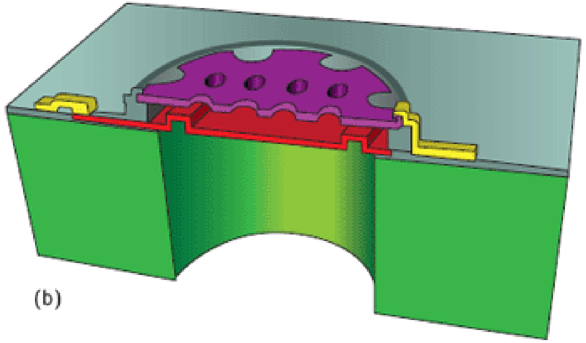


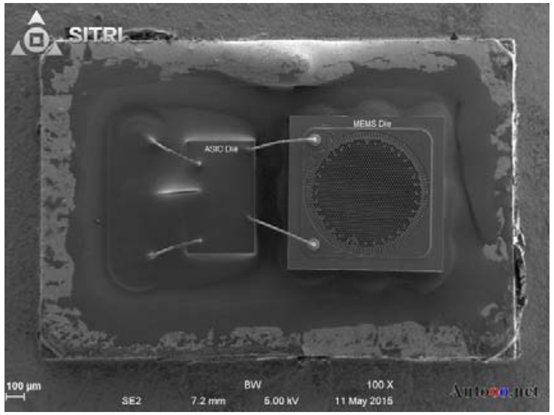


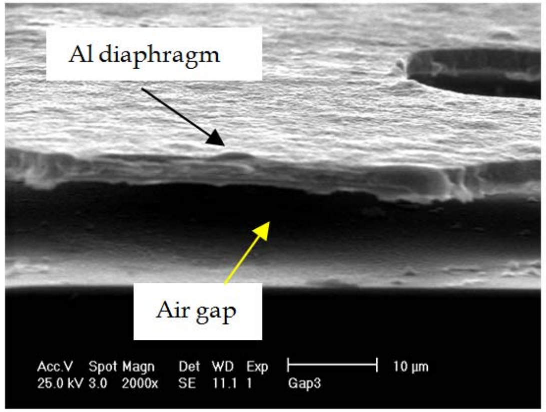


MICROPHONE – BULK / SURFACE MICROMACHINING (COMBO)

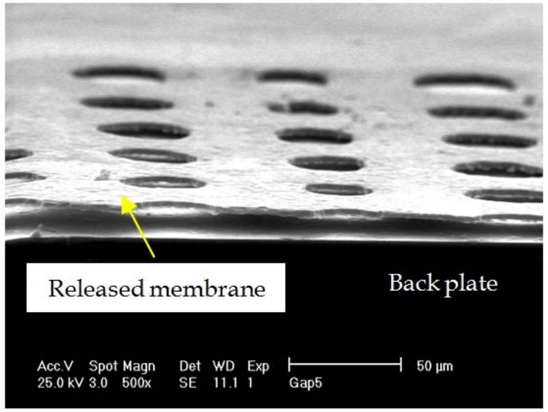




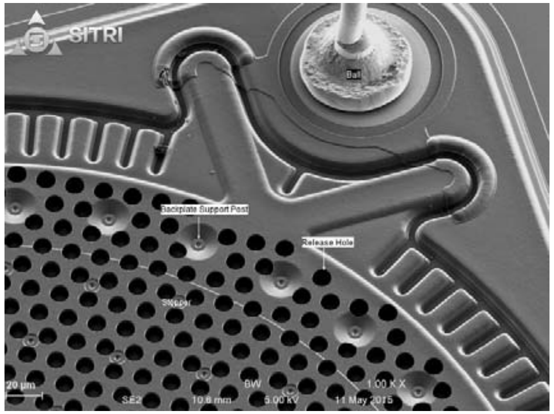




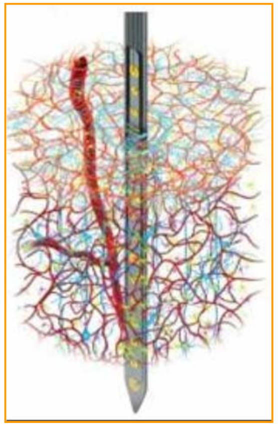
(a) Air gap of microphone

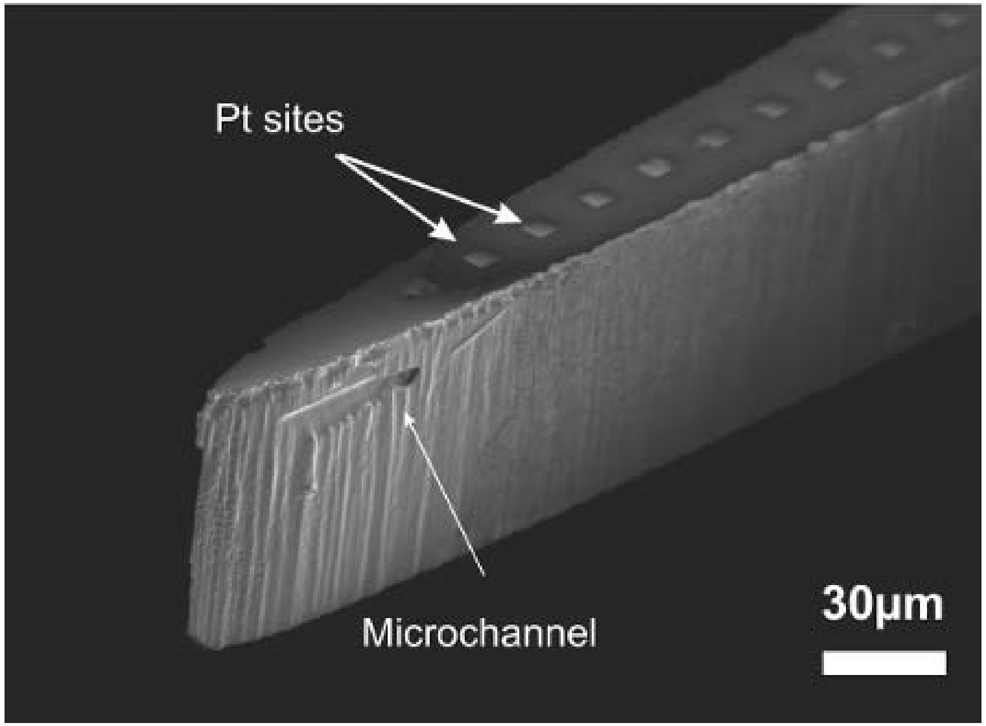


(b) Released membrane structure



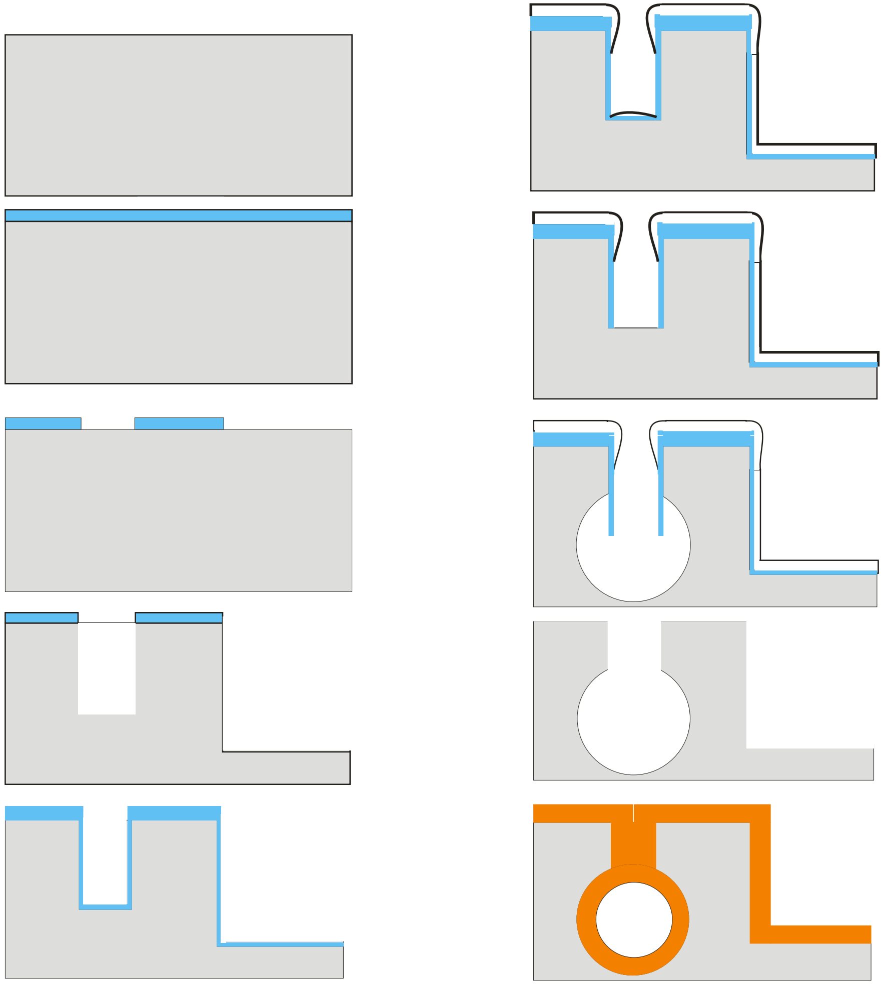
DRUG DELIVERY CHANNELS IN SILICON NEURAL PROBE

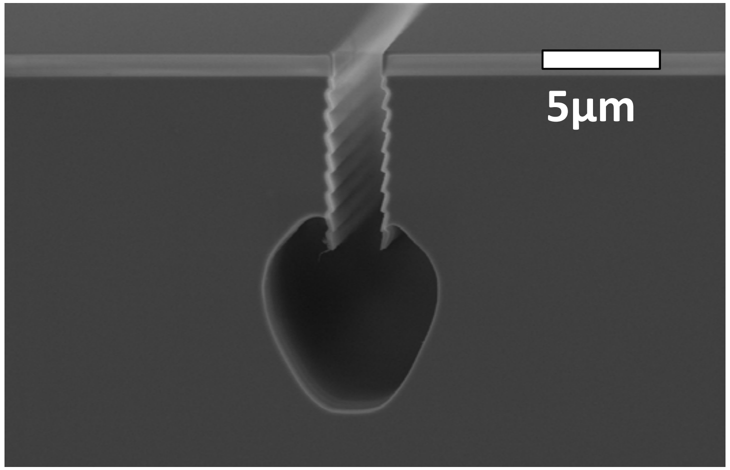


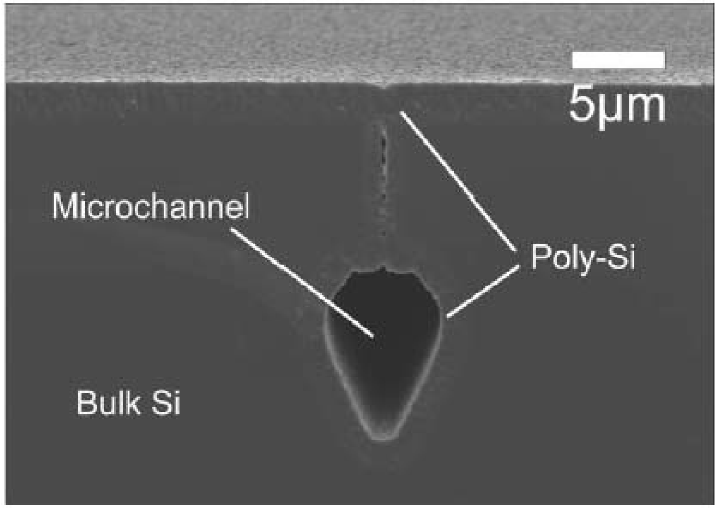


- High throughput channel array in a single substrate
- Utilysing the whole cross-section of the shaft
- Orientation independent positioning
- CMOS compatible fabrication technology
- High quality surface applicable for further lithographic steps

FABRICATION TECHNOLOGY OF BURRIED CHANNELS

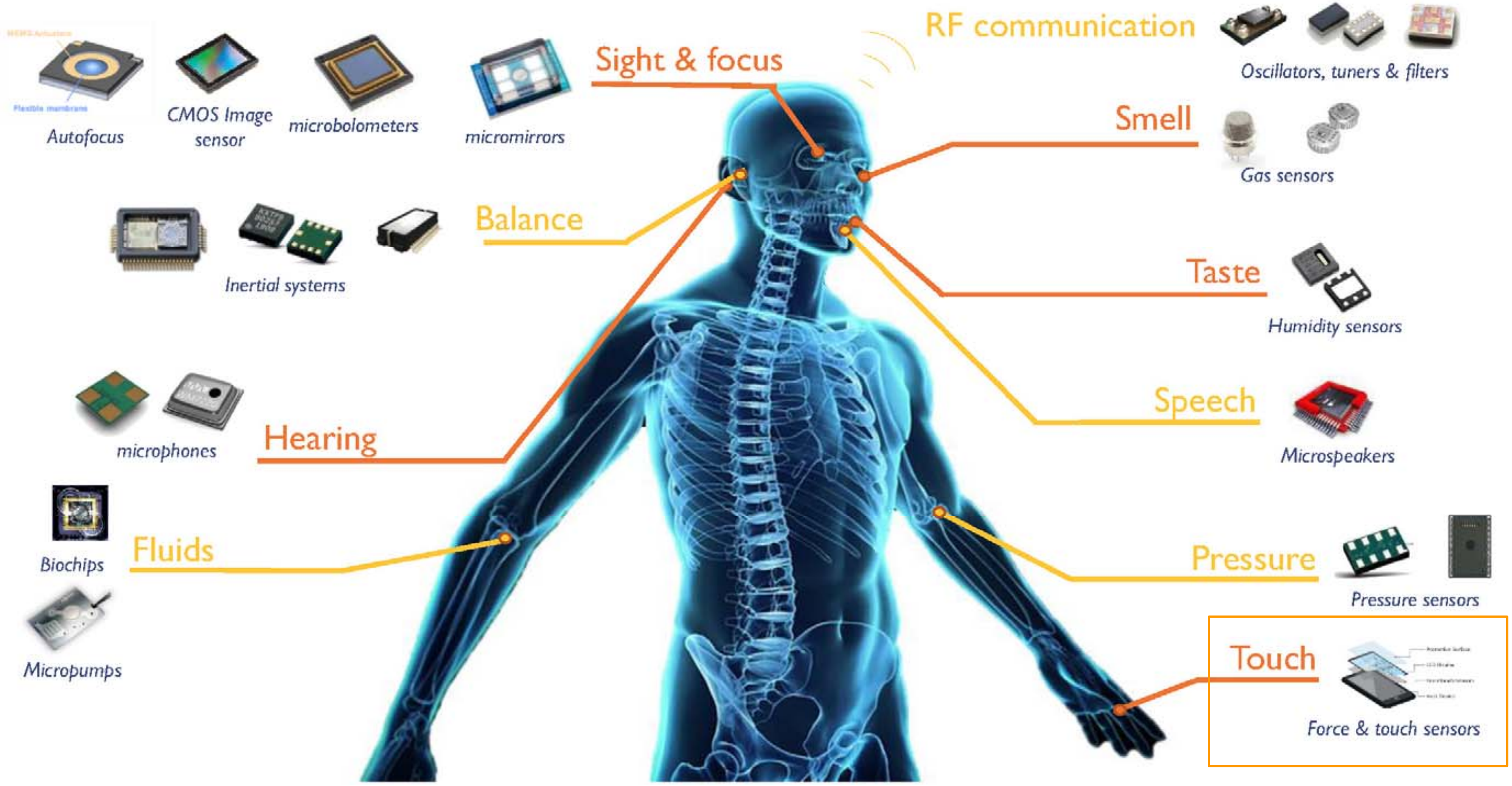






INTEGRATED MICROSYSTEMS

HOW to MIMIC HUMAN SENSING?



ARTIFICIAL TACTILE RECEPTORS

BIOMIMETIC FORCE DETECTION ANALOGY of TACTILE SENSING

- static pressure, low and high frequency vibration, SHEAR FORCES!!!
- lubricity, roughness, patterns, shape…

Sensors and Actuators A 179 (2012) 17–31

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journal homepage: www.elsevier.com/locate/sna

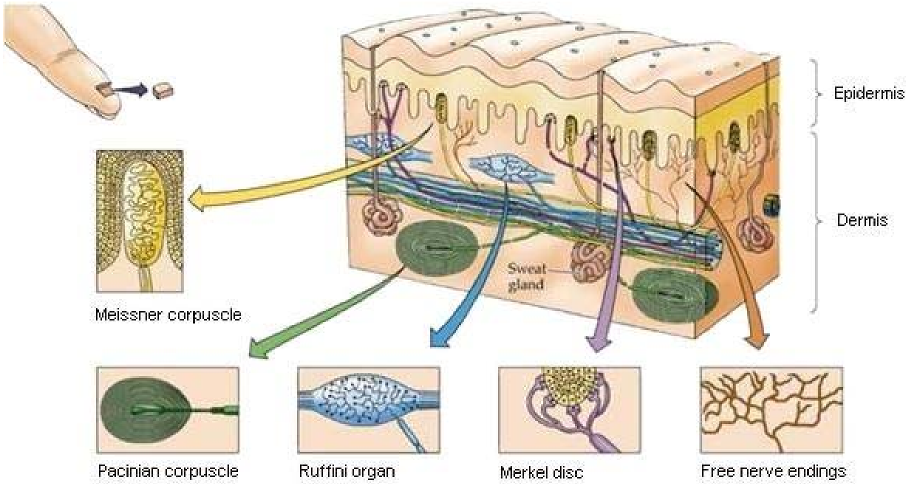
Review

A review of tactile sensing technologies with applications in biomedical engineering

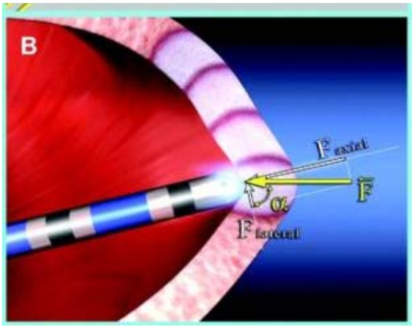
Mohsin I. Tiwana, Stephen J. Redmond, Nigel H. Lovell*

Graduate School of Biomedical Engineering, University of New South Wales, Sydney, NSW 2052, Australia

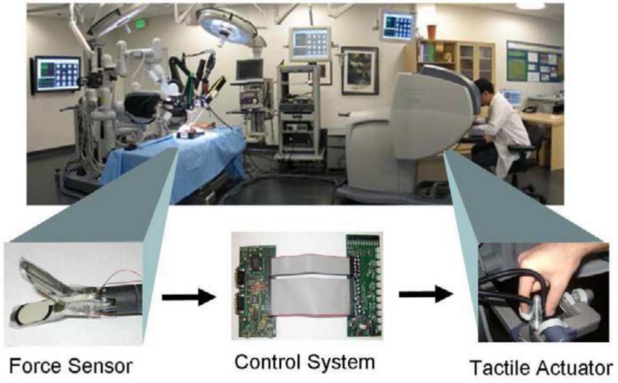
Human tactile receptors



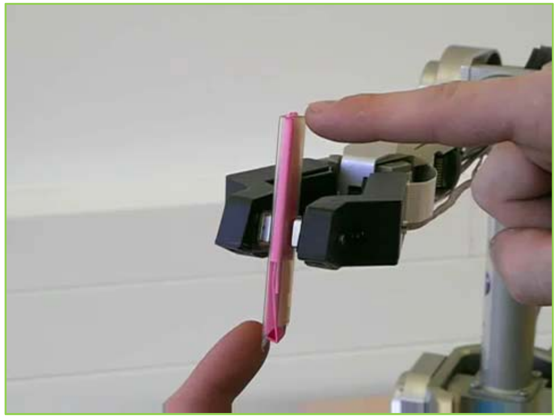
IN VIVO CONTACT FORCE MEASUREMENT



- visualization of contact force between catheter tip and the heart wall during catheter ablation
- Tactile (force) feedback during MIS surgery

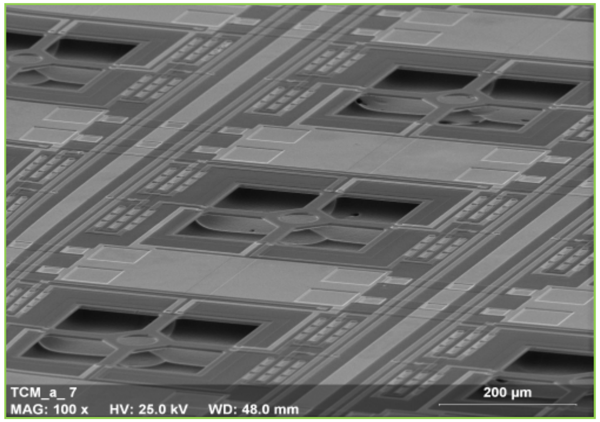


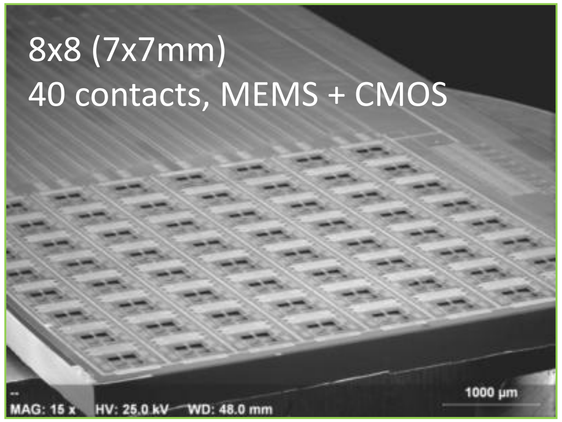
ARTIFICIAL TACTILE RECEPTORS



MEMS BASED 3D VECTORIAL μFORCE SENSOR

- **3D MEMS technology** based realisation of crystalline Silicon sensing elements
- **piezoresistive** read-out principle



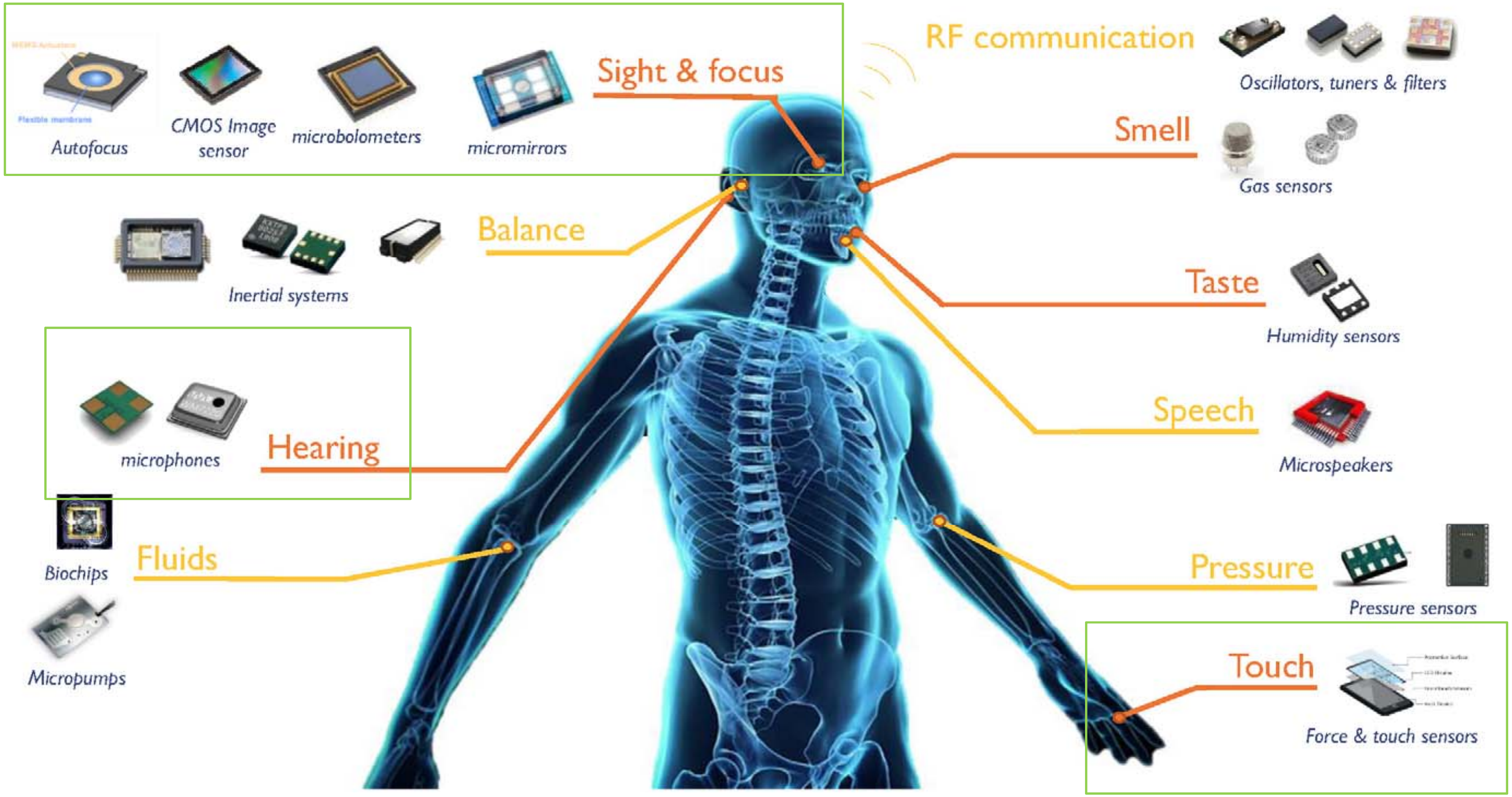

8x8 (7x7mm)
40 contacts, MEMS + CMOS


PDMS rubber hemispheres
as 1st level packaging

ACTUAL FEATURES

- sensitivity and resolution: similar to human fingers
- max. density: 8x8 taxels with CMOS addressing read-out circuitry
- neuromorph flexible polymer covering

HOW to RECOVER HUMAN SENSING OR FUNCTIONS?



Sight & focus
Autofocus
CMOS Image sensor
microbolometers
micromirrors

RF communication
Oscillators, tuners & filters

Smell
Gas sensors

Balance
Inertial systems

Taste
Humidity sensors

Hearing
microphones

Speech
Microspeakers

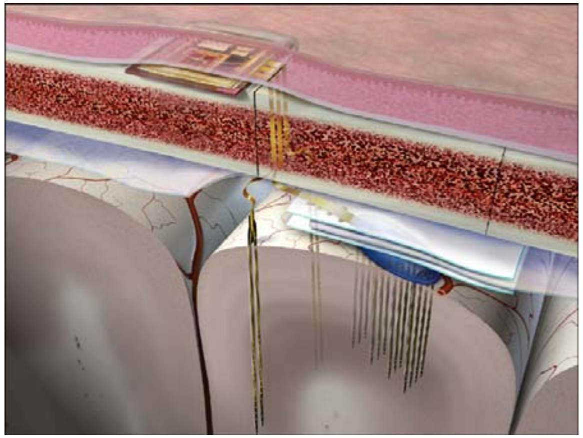
Fluids
Biochips
Micropumps

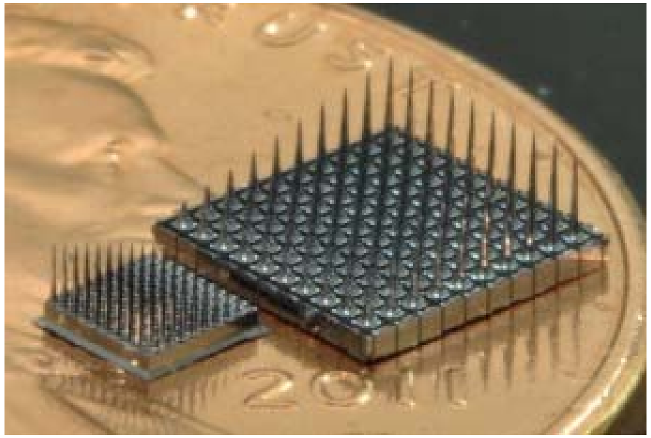
Pressure
Pressure sensors

Touch
Force & touch sensors

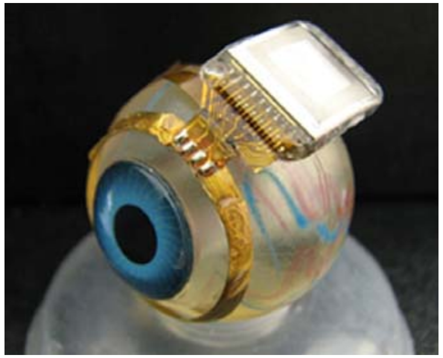
IMPLANTABLE MICROSYSTEMS

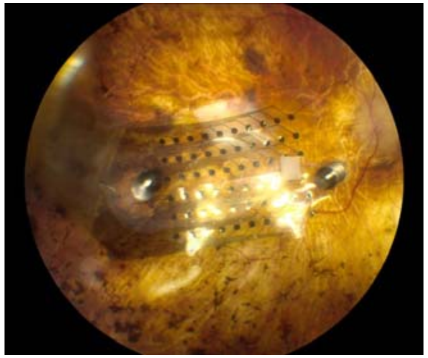
NEURAL CELL ACTIVITY RECORDING



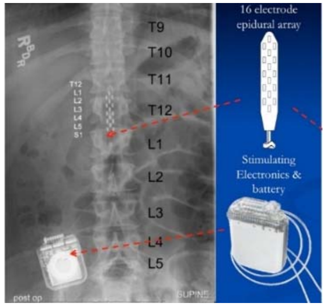


IMAGING

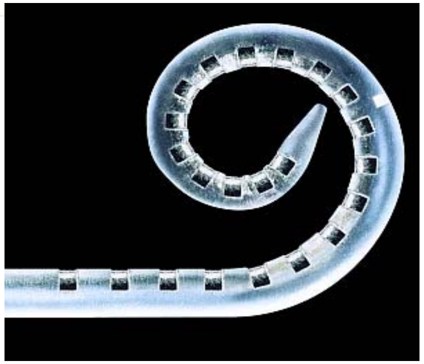




INTERFACING / STIMULATION



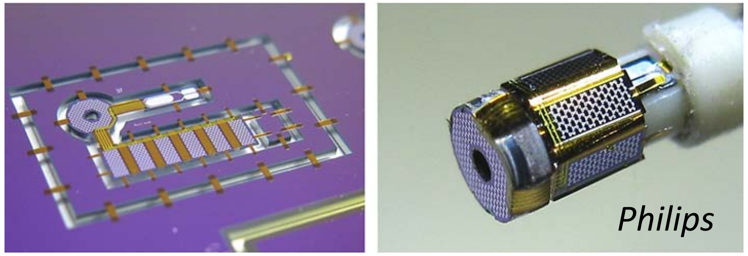
HEARING: COCLEAR IMPLANT



FUTURE TRENDS IN MEDICAL MEMS APPLICATIONS

SMART SYSTEMS – HIGH DENSITY INTEGRATION

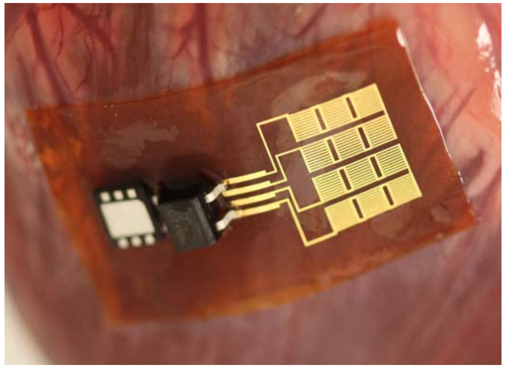
- Energy supply
- Sensing
- Signal / Data processing
- Communication
- Actuation


Philips

NANOTECHNOLOGY

- diagnostics & treating

IMPLANTABLE AUTONOMOUS DEVICES

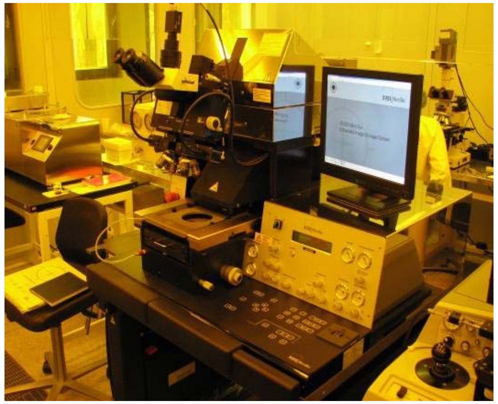

University of Illinois

- Energy harvesting
- SENSING: continous health monitoring
- ACTUATION: immediate treating (drug injection)
- INTERNET of THINGS

BRAIN-MACHINE INTERFACING

INTRO MTA EK MFA

MEMS LAB AT MTA EK MFA



MEMS laboratory:
300+150 m^2 clean room (4inch wafers) - 1mm resolution - mask shop (Heidelberg laser PG & direct writing),

Mask alligner / nanoimprinting system (Karl Süss MA 6, Quintel),
DRIE (Oxford Instruments Plasmalab 100),
Physical and chemical layer deposition techniques
(vacuum evaporation, sputtering, 2x4 diffusion tubes, LPCVD, ALD),
Wafer bonder (Karl Süss BA 6), ion implanter, etc.

Nanoprocessing and analysis / characterisation:
E-BEAM, FIB, SEM, TEM, AFM, XPS, EDX, Auger, SIMS

Zeiss-SMT LEO 1540 XB SEM,
Canion FIB nanoprocessing system
SEM and focused ion beam (FIB),
Gas injection system (GIS) (EBAD, IBAD)
and Energy Dispersive Spectroscopy (EDS)

Nanoprocessing and analysis / characterisation:
RAITH 150 E-BEAM

- Direct writing /
  mask processing - Ultra high resolution

- Thermal field emission (Schottky) source.
- GEMINI (state-of-the-art low kV
  performance, beam energy: 200 V – 30 kV.

- 6'' laser interferometer stage
- electrostatic clamping
- automatic sample levelling by 3-points piezo motor

- Writable surface: 0.5 – 800 μm
- Fixed Beam Moving Stage (FBMS)
- Fast Pattern Generator max. 10 MHz writing frequency
- Minimum dwell time: 2 ns.

- Measurement functions: linewidth and long-range laser interferometry based 2 nm resolution
- Magnifications: 20 – 900.000 X.

ACKNOWLEDGEMENT

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J. Prechl, K. Pap
Eötvös Loránd University, Immunology Dept.

BioMEMS Group:

www.biomems.hu

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SEVENTH FRAMEWORK PROGRAMME

SZÉCHENYI 2020

MAGYARORSZÁG KORMÁNYA

NEMZETI KUTATÁSI, FEJLESZTÉSI ÉS INNOVÁCIÓS ALAP

BEFEKTETÉS A JÖVŐBE

via **P3SENS / CAJAL4EU / INCITE / PAMIAQ / VKSZ_14** projects