Nano-devices

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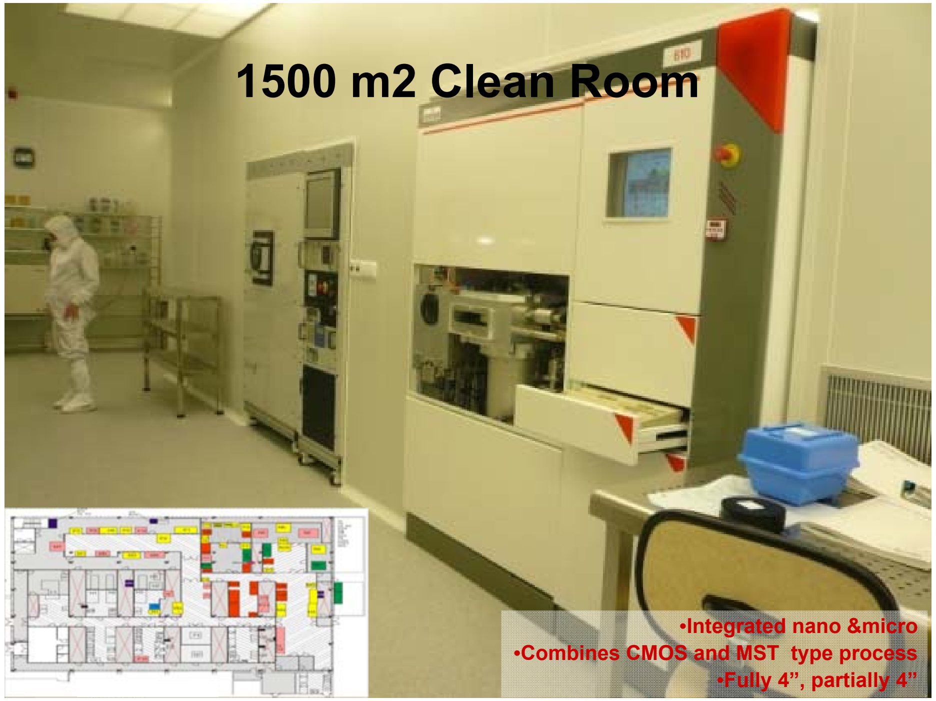
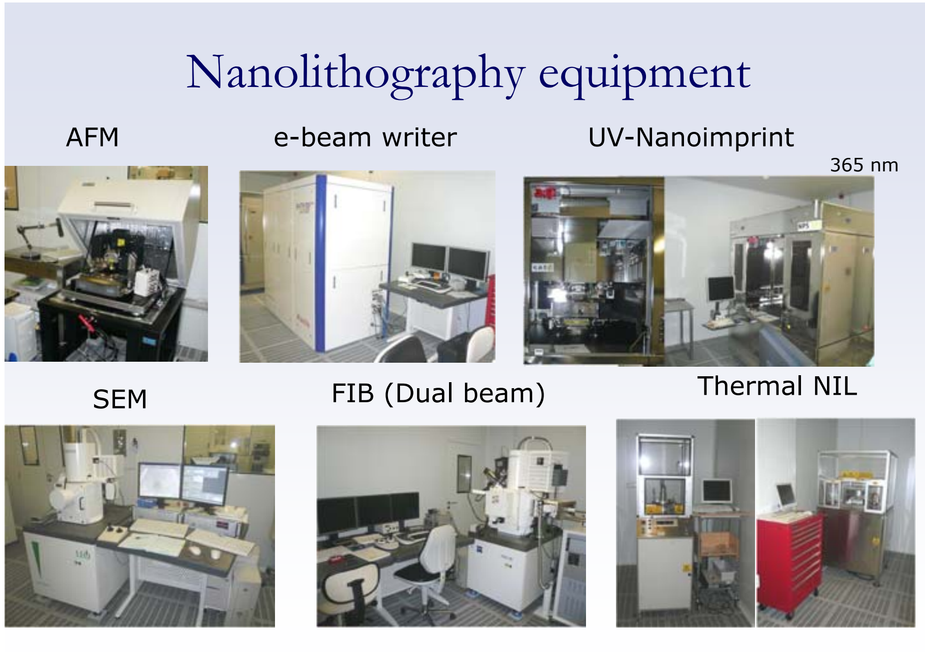
CSIC
20 m


1500 m2 Clean Room
•Integrated nano &micro
•Combines CMOS and MST type process
•Fully 4", partially 4"


Nanolithography equipment
AFM
e-beam writer
UV-Nanoimprint
365 nm
SEM
FIB (Dual beam)
Thermal NIL

Why reducing the dimensions of a device?

- Advantages:
  - **Speed (fast response time) / Sensitivity**
  - **Less energy consumption**
  - Save of space/Increase of integration
  - Save of material cost / Batch fabrication
- Scaling:
  - Need for adapted fabrication methods
  - At micro and nano scale, objects behave differently
    - Macroscopic scale: Water falls down from a glass facing down
    - Microscopic scale: Due to surface tension, water does not fall down from a glass facing down

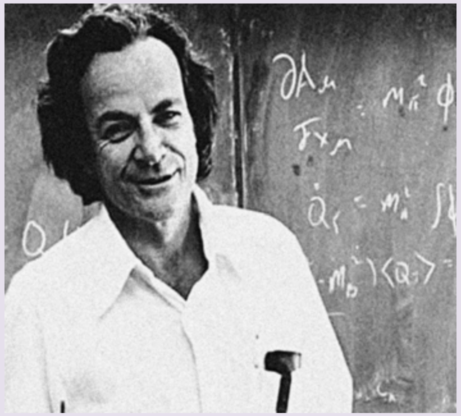
Miniaturization in electronics:

The technology that has most influenced life during the last 60 years

Computers

Communication

Entertainment



Richard P. Feynman. Physicist. 1918-1988

1959: There is plenty of room at the bottom

"(…)computing machines are very large; they fill rooms. Why can't we make them very small, make them of little wires, little elements---and by little, I mean little. For instance, the wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across."

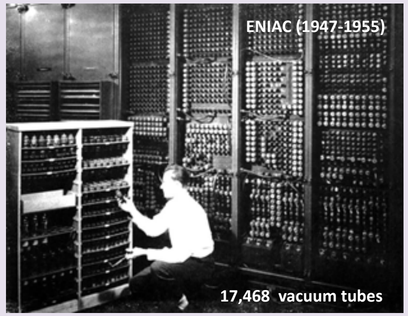
Gordon E. Moore, Chemist (1929-)

1965: "Cramming more components onto integrated circuits"

"The future of integrated electronics is the future of electronics itself. (…) Integrated circuits will lead to such wonders as home computers, or at least terminals connected to a central computer, automatic controls for automobiles, and personal portable communications equipment"

Vacuum tubes vs transistor

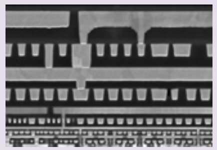
https://en.wikipedia.org/wiki/Vacuum_tube



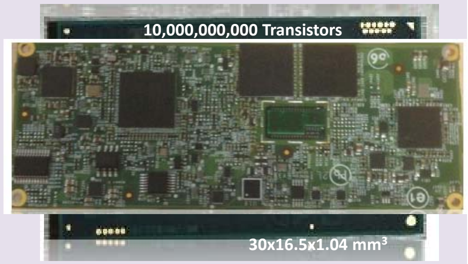
1947 First transistor

2015 Transistor (14 nm)

1958 (integrated circuit)



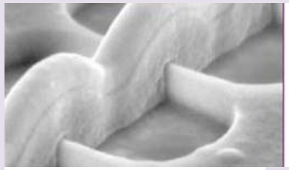
2015 Integrated circuit

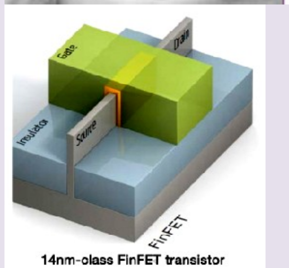


2015 Intel® Core™ M

The Transistor

Miniaturized Switch





Some features:

- Transistor Fin Pitch: 42 nm
- Transistor Gate Pitch: 70 nm
- Interconnect Pitch: 52 nm
- 0.0588 um^2 SRAM cell
- Approx: 10 billions transistors /microprocessor
- Frequency: 4 GHz

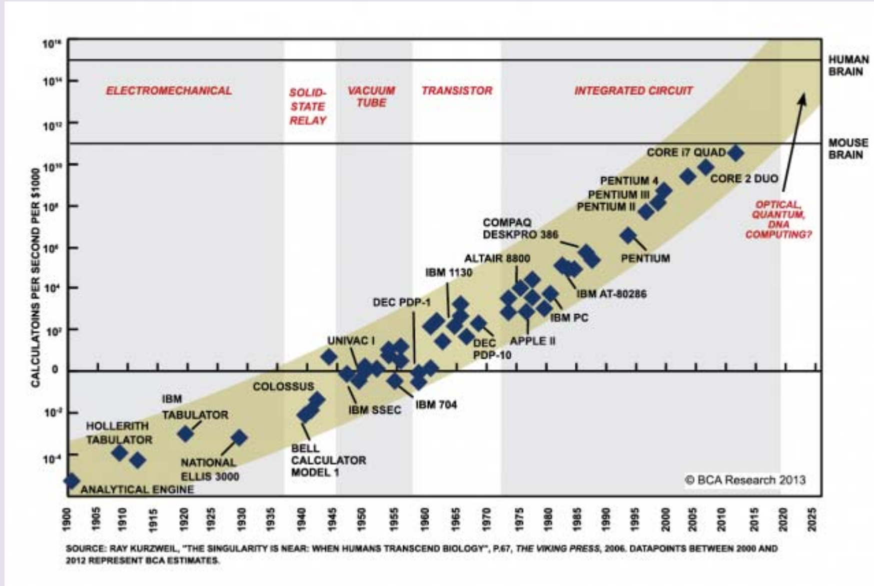
THE NANO DEVICE !!

Dimensions: 10 nano-metres

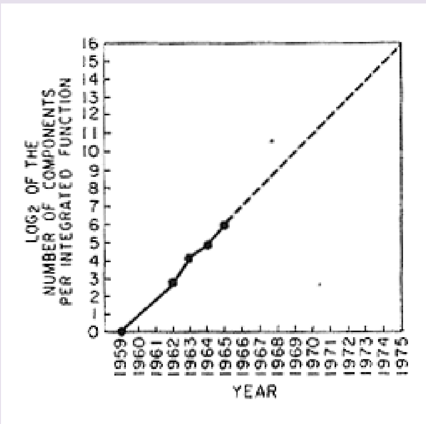
Switching time: 0.1 nano-seconds

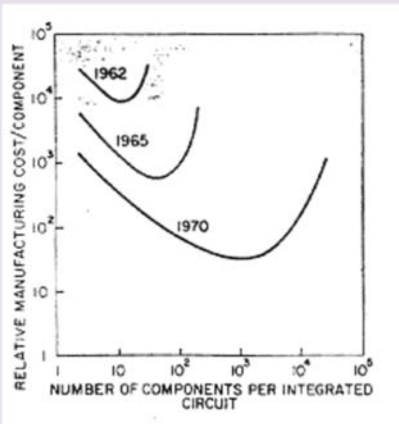
Number of transistors: 10^9

Computer performance



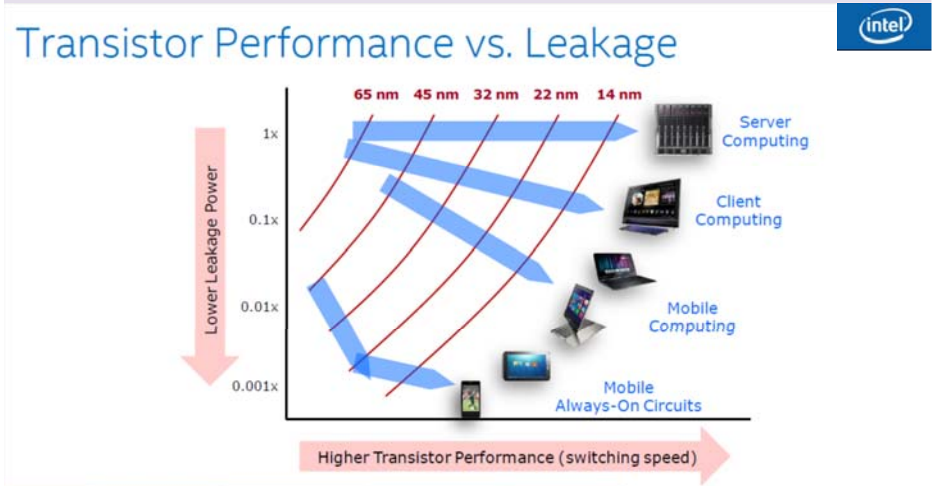
Moore's law



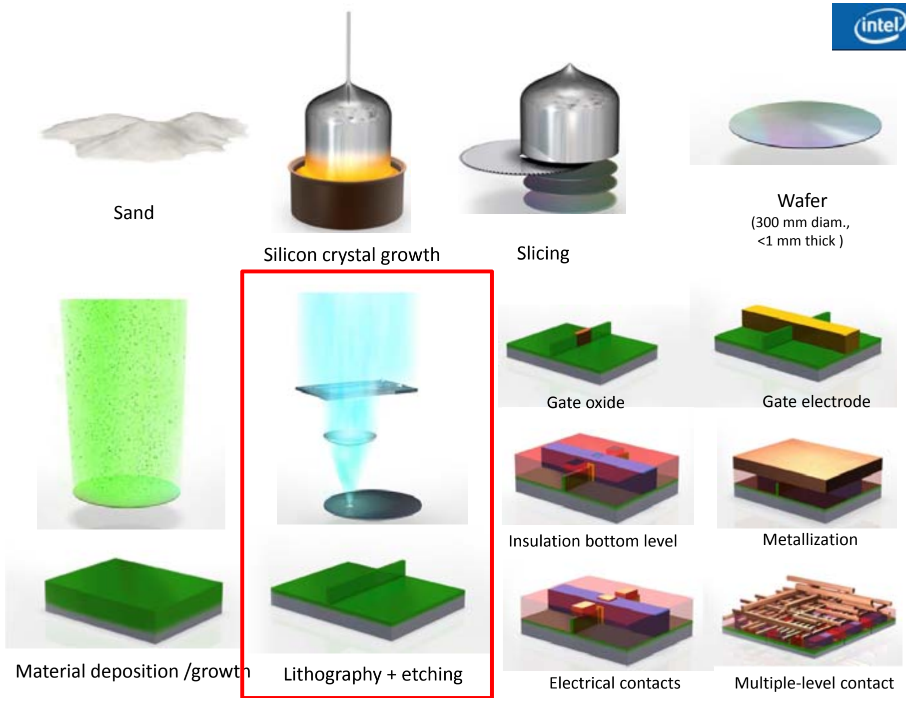


Gordon E. Moore. *Craming more components onto integrated circuits* . Electronics, Volume 38, Number 8, April 19, 1965

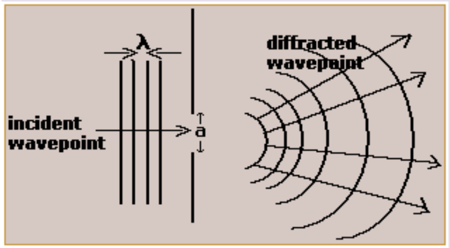
Power consumption



How integrated circuits are fabricated?



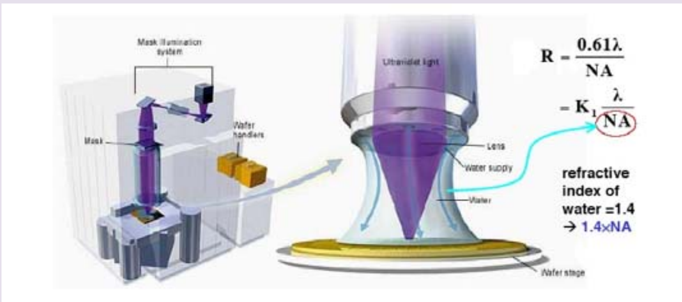
Diffraction limits resolution



$$R = k1\,\frac{\lambda}{NA}$$

K_1=0.22, λ= 193 nm, NA=1.35

Resolution= 32 nm



Today's lithography equipment

Price: approx 100 M€

Double patterning techniques

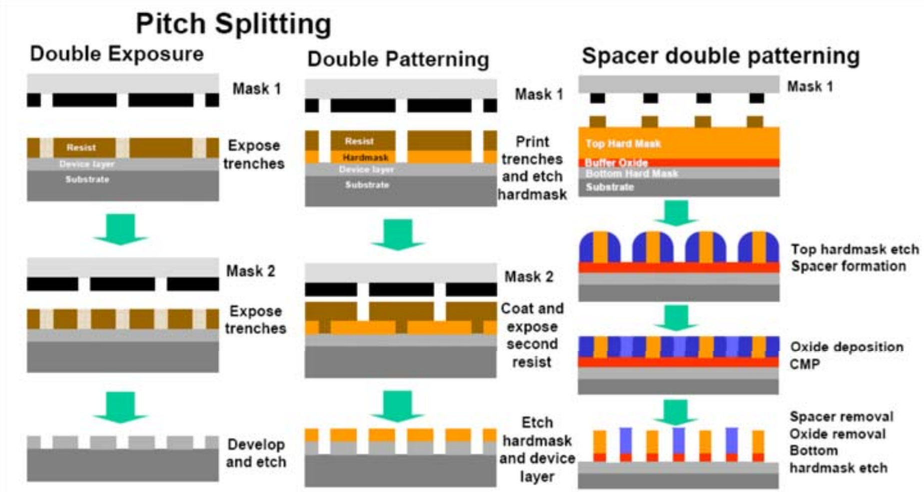
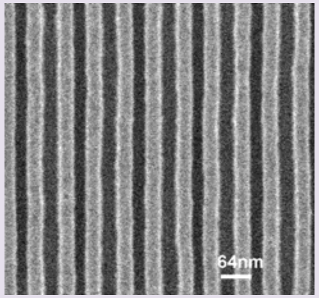


Figure LITH1 Process Flows for Pitch Splitting (DE, DP), and Spacer Patterning

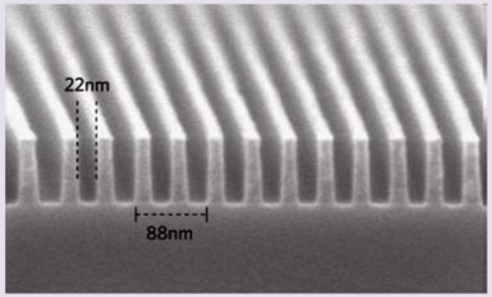
11 nm channgel length achievable with immersion lithography

Double patterning techniques



32nm half-pitch poly-Si gates etched using double pattering

© IMEC



Self-aligned double patterning 22 nm half pitch

© Applied Materials

News & Analysis

TSMC to Adopt Extreme Ultraviolet at 5nm

EE Times Connecting the Global Electronics Community

Alan Patterson
7/14/2016 11:10 AM EDT
5 comments

Like 62 Tweet Share 285 G+1 6

TAIPEI—Taiwan Semiconductor Manufacturing Co. (TSMC), the world's largest foundry, said it will fully implement extreme ultraviolet (EUV) lithography to make 5nm chips by the end of this decade.

"We estimate that EUV will be a cost-effective tool for high-volume manufacturing by 2020, in time for our 5nm ramp," TSMC Co-CEO Mark Liu said at an event to announce the company's second-quarter results. "We plan to use EUV lithography extensively in 5nm to improve density, simplify process complexity and reduce cost."

The company said it has been using 7nm as a development vehicle for EUV, achieving what it called good integration of EUV scanners, masks and photoresist. TSMC said it is running four state-of-the-art EUV scanners for infrastructure development and will move in another two NXE:3400 EUV production tools from ASML in the first quarter of 2017.

EE Times Connecting the Global Electronics Community

Advanced nodes
In other nodes that are yet to reach commercial production, TSMC provided a progress update.

TSMC said it will see its first revenue from 10nm during the first quarter of 2017, and it expects 10nm to ramp steeply throughout next year.

"Our 10nm has been transferred from R&D to production," Liu said. "Our first 10nm customer product has been produced with satisfactory functional yield. So far, three customer products have been taped out to us."

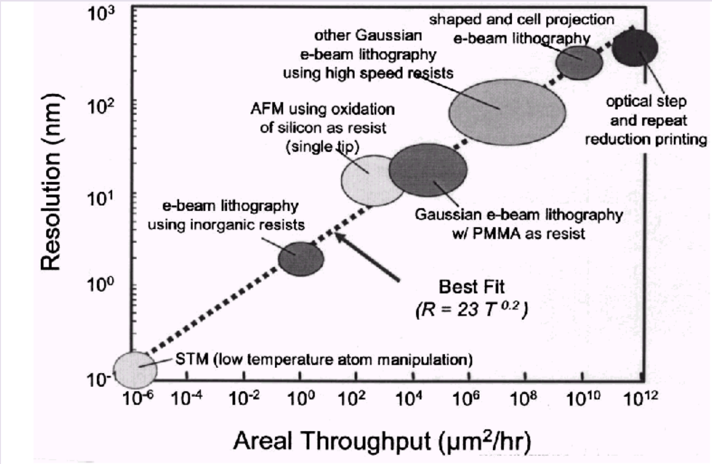
At the 7nm node, TSMC said its yield improvement on a 256 megabit SRAM test device is ahead of schedule.

"We believe our 7nm power, performance and area density (PPA) is ahead of our competitors," Liu said. TSMC's mobile and high-performance computing customers "all have aggressive product tape out plans in the first half of 2017 with volume production planned in early 2018," he added.

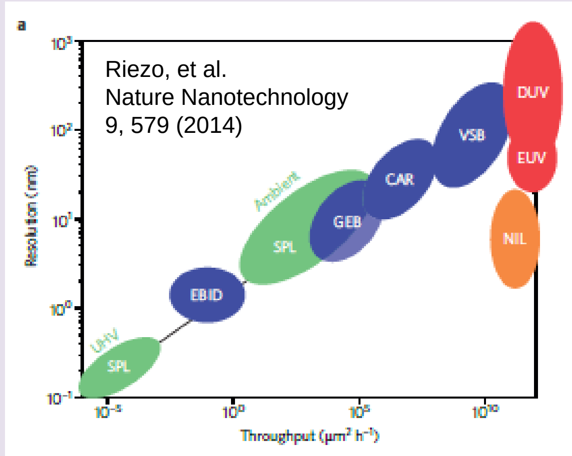
Nanolithographies:

Resolution vs Throughput

Nanotechnology, D. M. Tennant . AIP/Springer, New York, 1999



Nanolithographies: Present status



SPL: Scanning Probe Lithography

EBID: Electron Beam Induced Deposition

GEB: Gaussian Beam Electron Beam Lithography

CAR: Chemical Amplified Resists Electron Beam Lithography

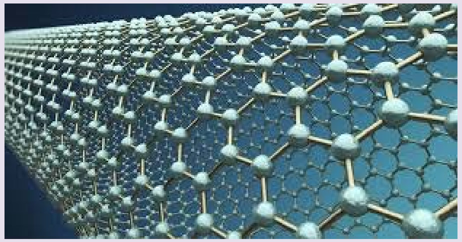
VSB: Variable Shape Beam Electron Beam Lithography

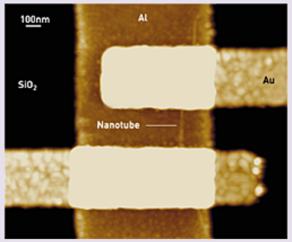
DUV: Deep UV Optical Lithography

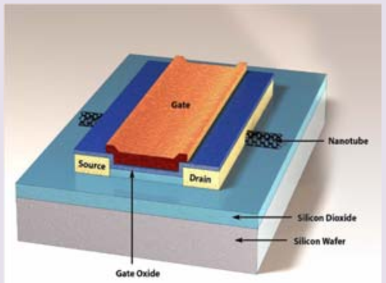
EUV: Extreme UV Optical Lithography

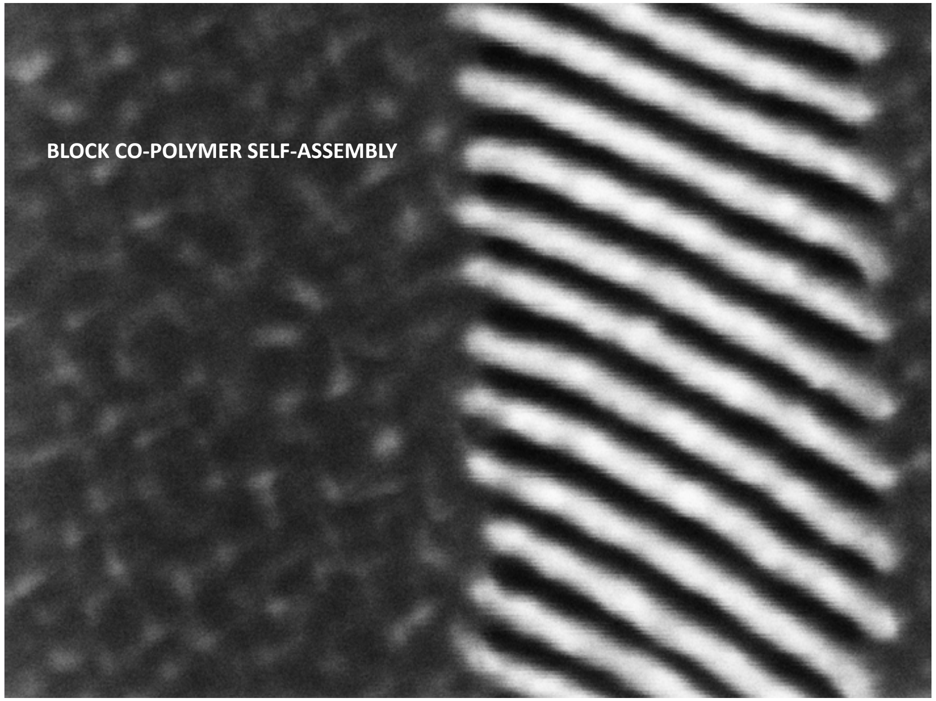
NIL: Nanoimprint Lithography

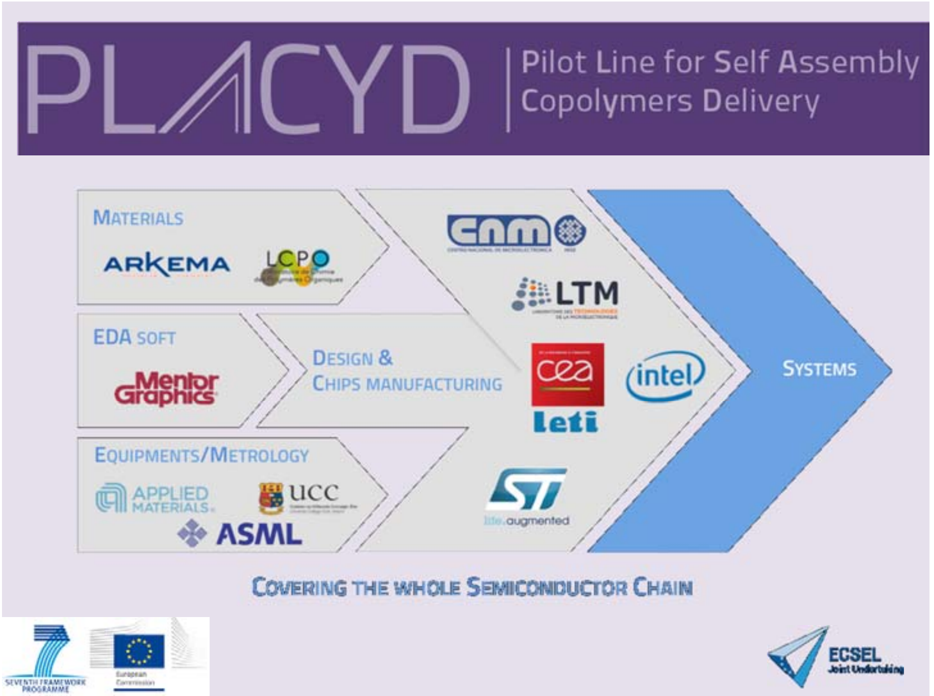
Bottom-up fabrication



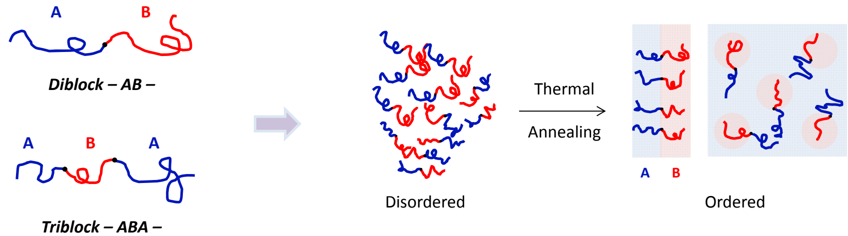




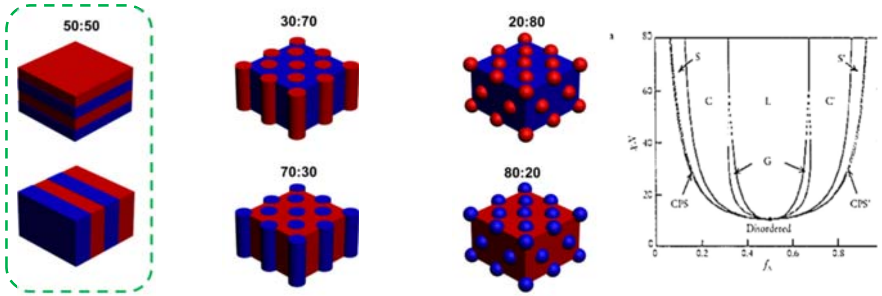




Block co-polymer self-assembly

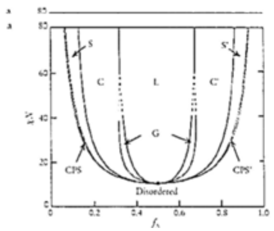


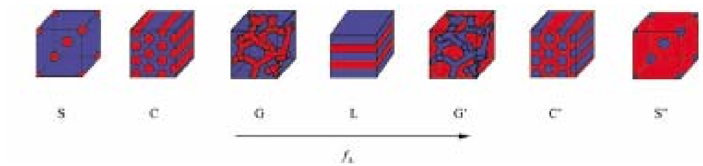
→ The **morphology of the BCP** depends on the **ratio** between the **molecular weights** of both blocks:



Phase separation in block copolymers

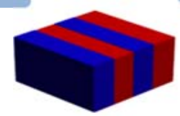
- The propensity for block copolymers to phase separate into periodic microdomains is determined by the strength of the repulsive interaction
- It is characterized by the product χN:
    - χ is the Flory-Higgins interaction parameter
    - N is the number of monomers in the diblock copolymer
- Microphase separation can occur when χN exceeds the critical value for the order-disorder transition.
- At equilibrium, this microphase separation is established by the energy balance between the stretching energy for the polymer chains and the energy of interactions at the interface between A and B microdomains.





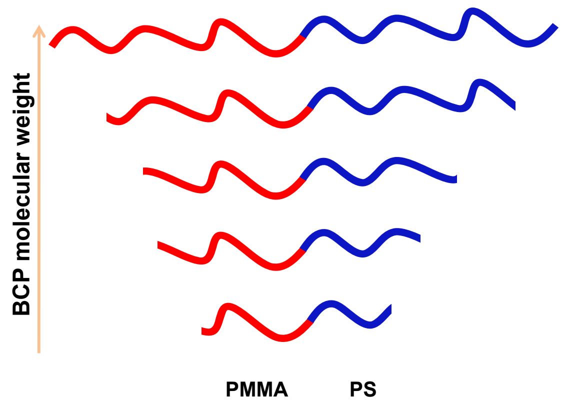
BLOCK CO-POLYMER SELF ASSEMBLY

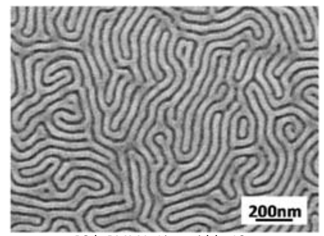
→ The **block copolymer pitch** (L_0) depends on its **molecular weight.**



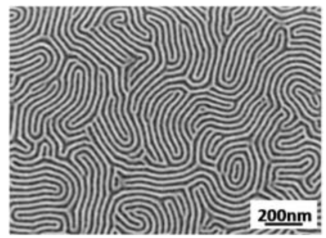
Vertical Lamella

Polymer chain length = Polymer period



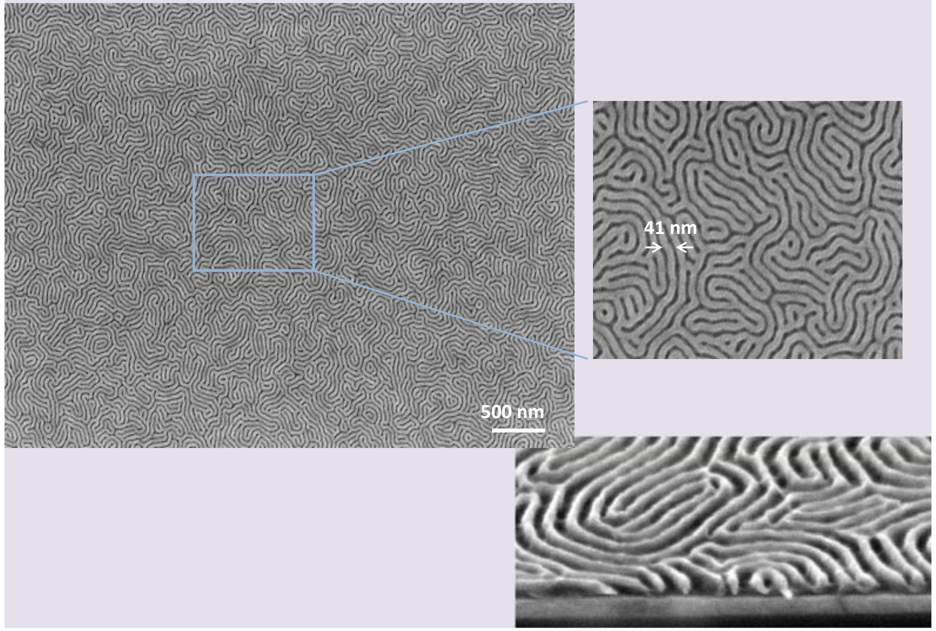


PS-b-PMMA. Line width: 18 nm

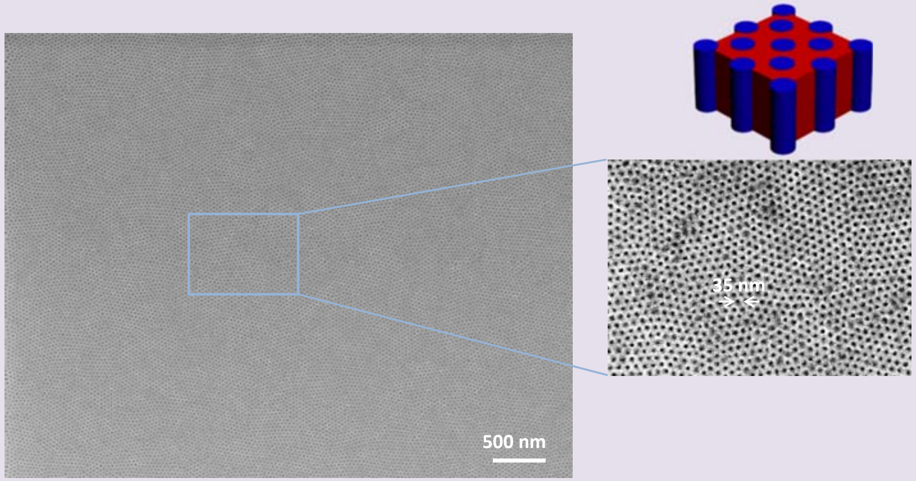


PS-b-PMMA. Line width: 11 nm

Examples of phase segregation

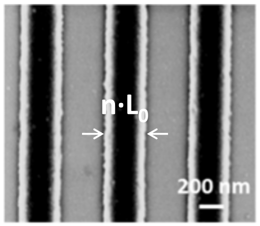


Examples of phase segregation



DIRECTED SELF – ASSEMBLY OF BLOCK COPOLYMERS

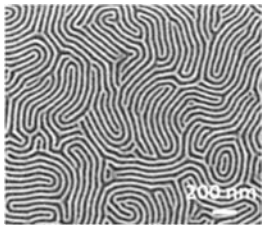
Traditional lithographic techniques



EBL
DUV
EUV

+

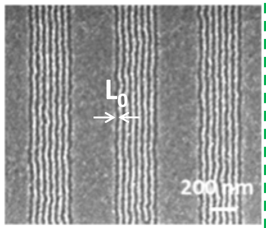
Intrinsic property of BCP to self-assemble



PS-b-PMMA
PS-b-PLA
PS-b-PDMS

=

Guiding of the BCP

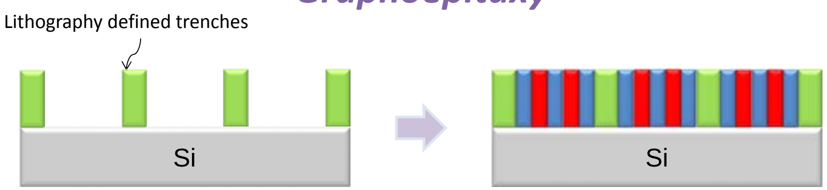


Chemical epitaxy
Graphoepitaxy

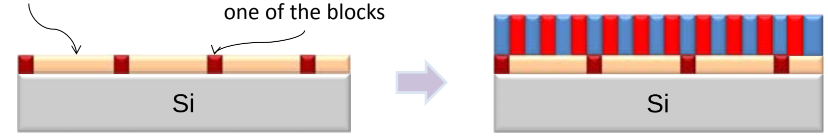
n: Density multiplication factor

DIRECTED SELF-ASSEMBLY METHODS

Graphoepitaxy



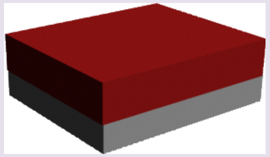
Chemical epitaxy



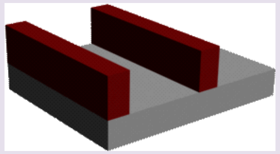
Graphoepitaxy process

LAMELLA

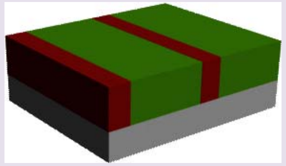
193nm resist deposition



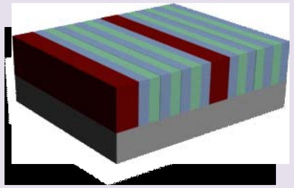
193nm lithography



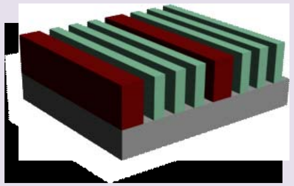
Block copolymer deposition



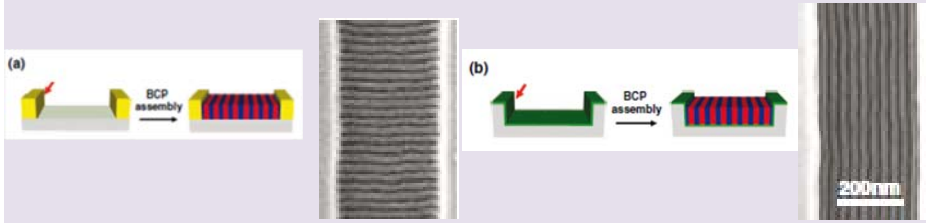
Self-assembly after annealing



MMA domain removal



Examples of grapho-epitaxy



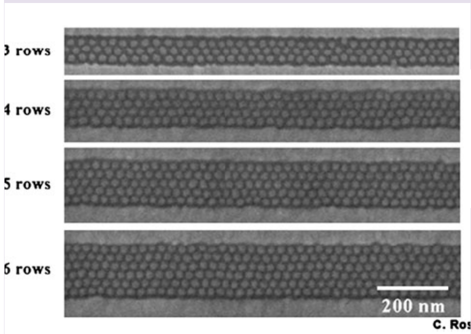
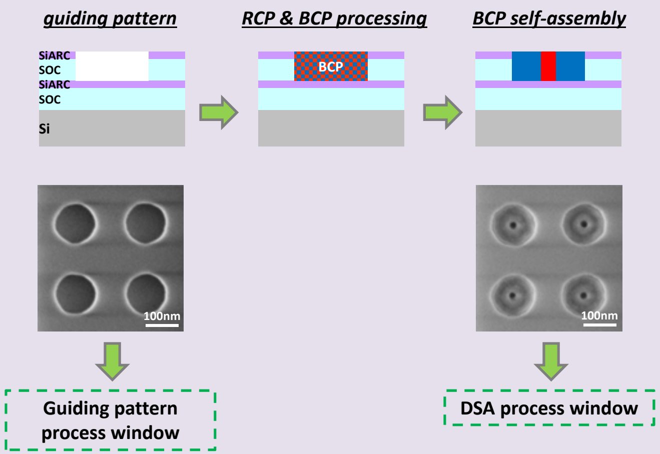


FIG. 4. Lithographically templated assembly of a polystyrene–polyferrocenyldimethylsilane (PS–PFS) diblock copolymer into a regular array of close packed structures, exhibiting short- and long-range order. Photographs courtesy of the research group of Ross and Chuang, Massachusetts Institute of Technology, adapted from Cheng, Nature Materials, 3(11), 824 (2004), used with permission.

Directed block copolymer self-assembly for nanoelectronics fabrication.
Daniel J.C. Herr.
J. Mater. Res., 26, 122, , 2011

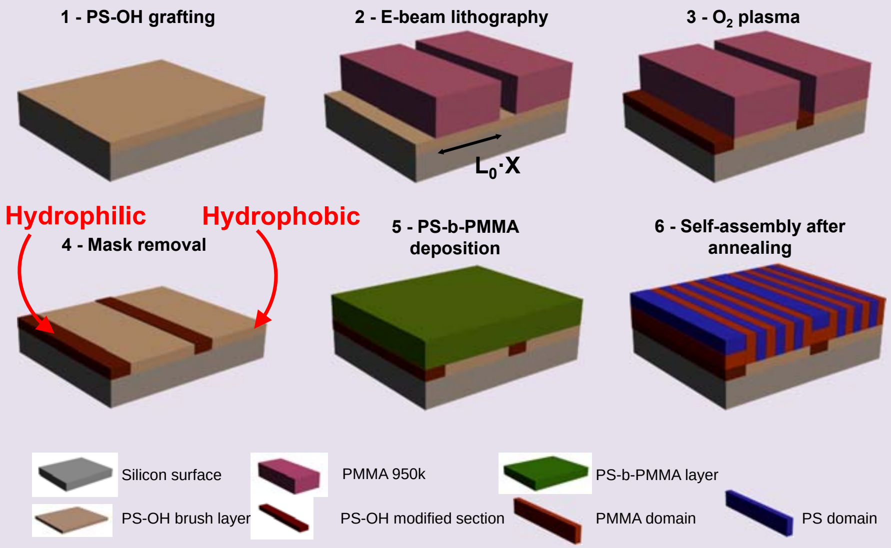
Graphoepitaxy process

Cillinders (Contact Shrink)



Tiron, R., et al. "The potential of block copolymer's directed self-assembly for contact hole shrink and contact multiplication." *SPIE Advanced Lithography*. International Society for Optics and Photonics, 2013.

Chemical epitaxy process (i)



Chemical epitaxy process (ii)

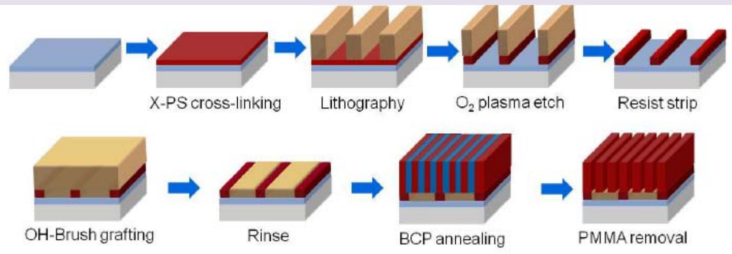
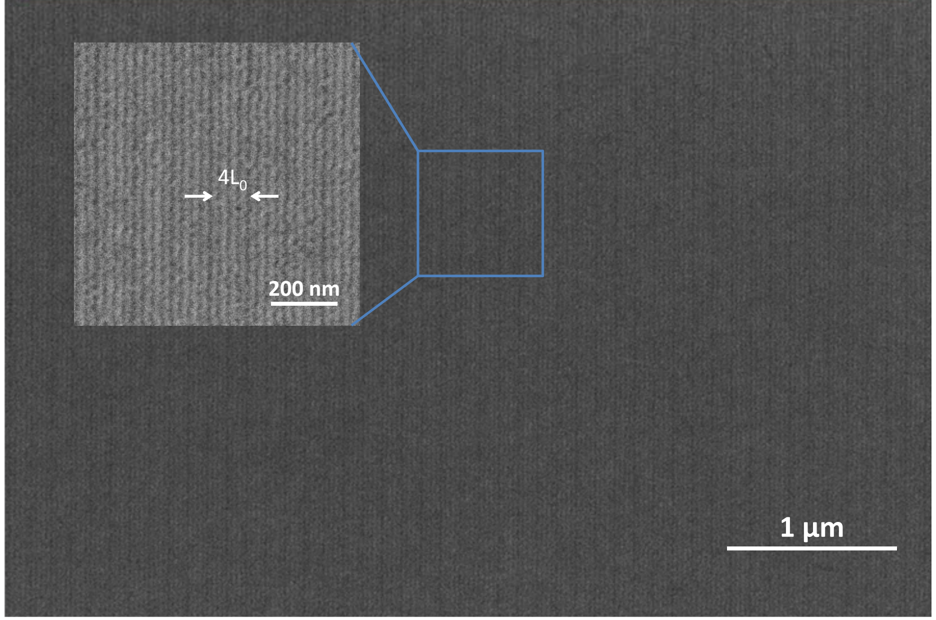


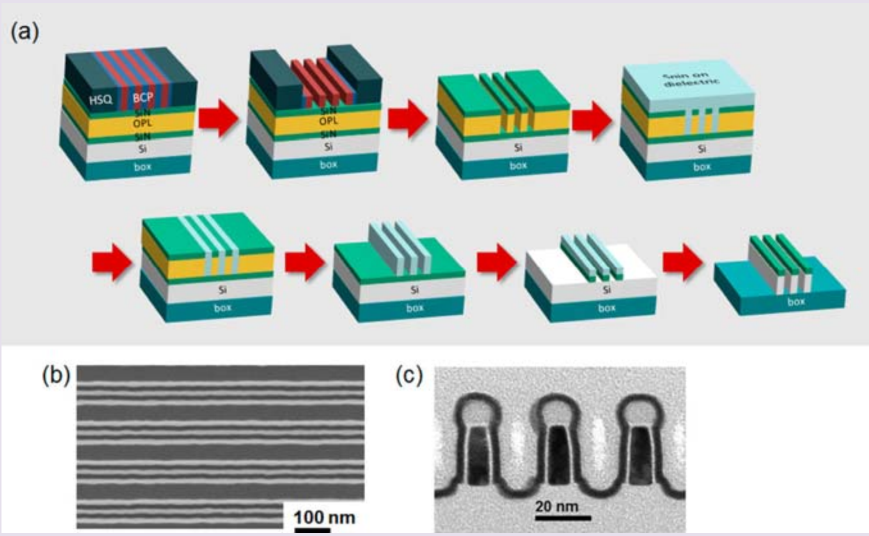
Figure 1. Schematic overview of the LiNe chemo-epitaxy process flow.

Defect reduction and defect stability in IMEC's 14nm half-pitch chemo-epitaxy DSA flow [9049-4]
R. Gronheid, P. Rincon Delgadillo, H. Pathangi, D. Van den Heuvel, D. Parnell, B. Chan, Y.-T. Lee, L. Van Look, Y. Cao, Y. Her, G. Lin, R. Harukawa, V. Nagaswami, L. D'Urzo, M. Somervell, P. Nealey

Examples of chemical epitaxy



Two-Dimensional Pattern Formation Using Graphoepitaxy of PS-b-PMMA Block Copolymers for Advanced FinFET Device and Circuit Fabrication

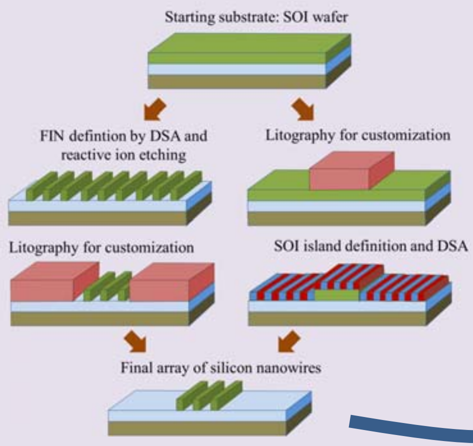


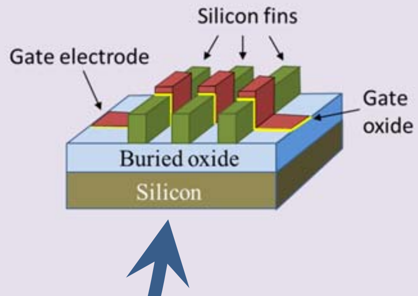
H. Tsai et al. Nanoletters 8, 5227 (2014) (IBM)

DIRECTED SELF – ASSEMBLY OF BLOCK COPOLYMERS

DEVICE FABRICATION

Integration **FINFET Array**





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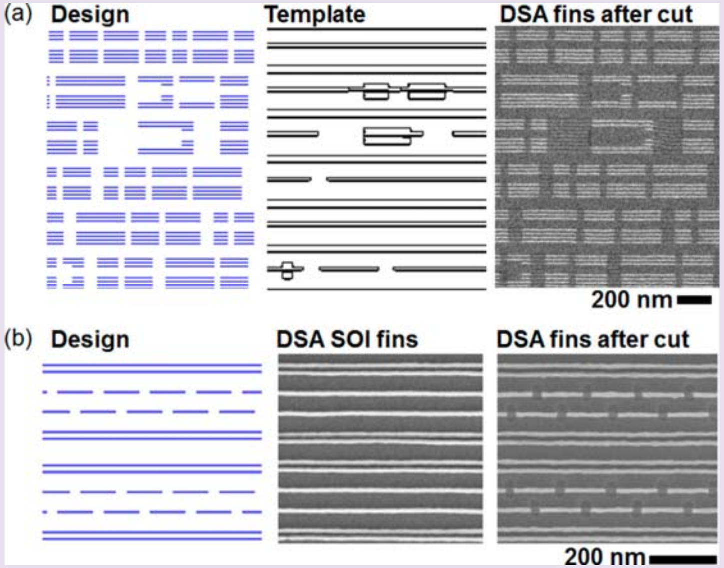
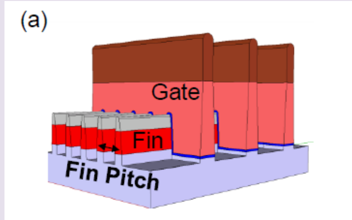
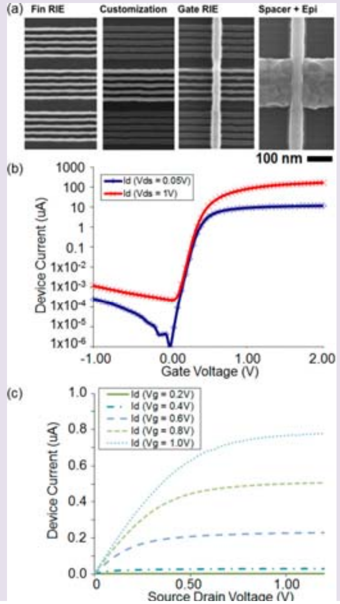


H. Tsai et al. Nanoletters 8, 5227 (2014) (IBM)

Two-Dimensional Pattern Formation Using Graphoepitaxy of PS-b-PMMA Block Copolymers for Advanced FinFET Device and Circuit Fabrication





H. Tsai et al. Nanoletters 8, 5227 (2014) (IBM)

Applications

Bit patterned media

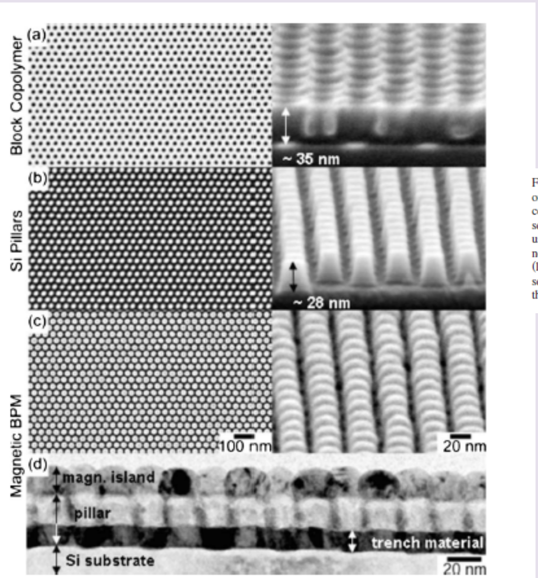
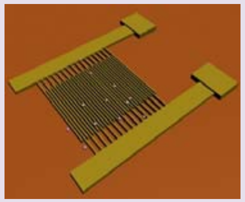
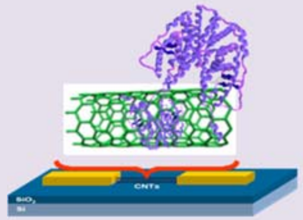


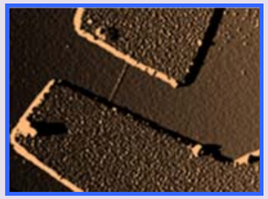
FIG. 1. 0.5 Tbit/in² (L_o=38 nm) BPM array consisting of MLs deposited onto Si pillar substrates fabricated via e-beam directed assembly of block copolymer films. SEM micrographs of (a) the block copolymer film after selective removal of the PMMA cylinder cores, (b) Si pillars after Cr lift-off using the template in (a) and subsequent reactive ion etching, and (c) magnetic BPM after depositing a Co/Pd ML thin film onto the pillar structures (left: top view, right: section view at 85° angle). (d) Bright field TEM cross-sectional image through two consecutive rows of bits (into the image plane) that are 180° phase shifted with respect to each other.

Appl.Phys.Lett. 96, 052511 (2010)

Nano-Sensors

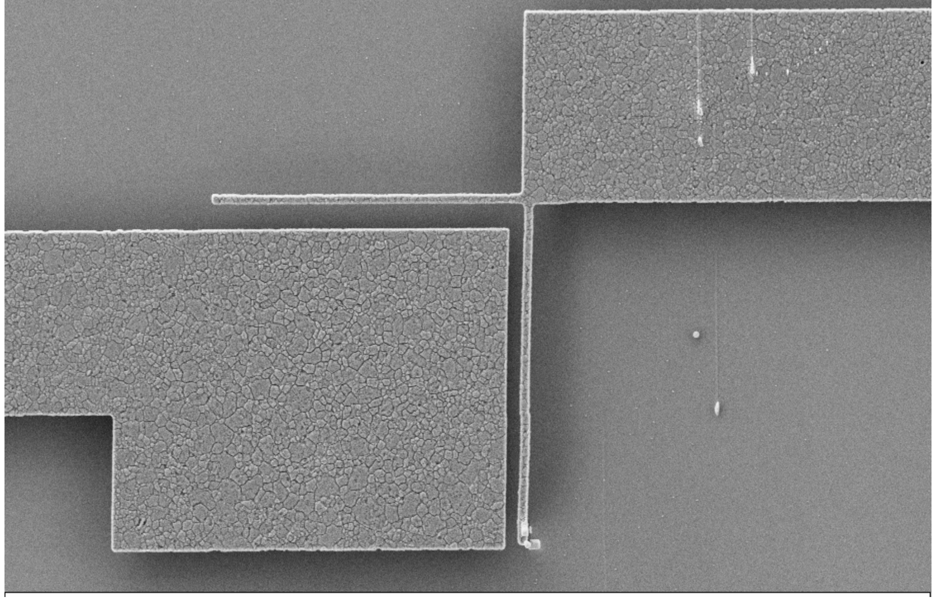




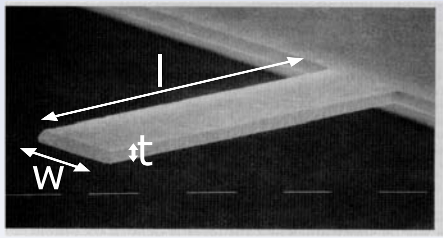


Nanoelectrodes **Nanotubes** **Cell pressure sensor**

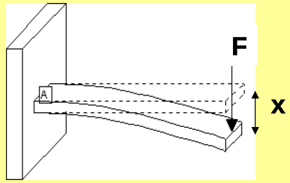
Nanomechanical sensors



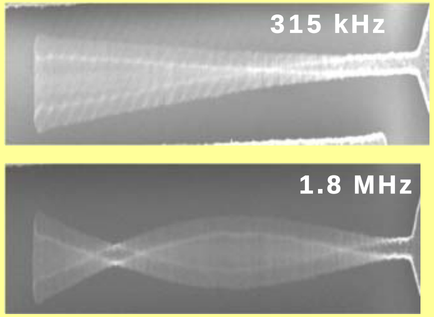
Simplest mechanical structure: cantilever



Elastic constant: ***k = F / x***

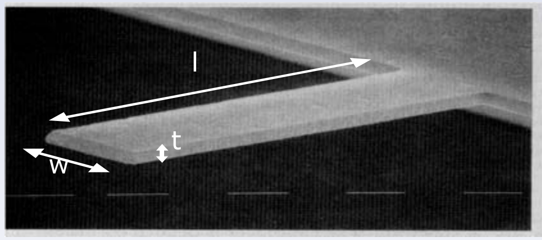


Resonance frequency



Zachary Davis. MIC-DTU

Mechanical properties as a function of dimension



$F = k\,x$

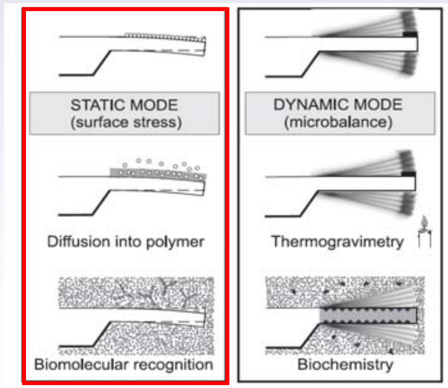
$$k = \frac{E}{4}\cdot\frac{t^3 \cdot w}{l^3} \quad \text{(N/m)}$$

$$f_{res} = 0.162\cdot\sqrt{\frac{E}{\rho}}\cdot\frac{t}{l^2} \quad \text{(Hz)}$$

Cantilever	l (μm)	w (μm)	t (μm)	k (N/m)	f_o	m_{eff} (g)
Soft	450	50	2	0.2	14 kHz	$2.5\cdot10^{-8}$
Stiff	125	30	4	44	364 kHz	$8.4\cdot10^{-9}$
Sub-micro	10	0.5	0.1	0.02	1.4 MHz	$2.8\cdot10^{-13}$
Nano	1	0.5	0.1	20	134 MHz	$2.8\cdot10^{-14}$

Static versus dynamic mode

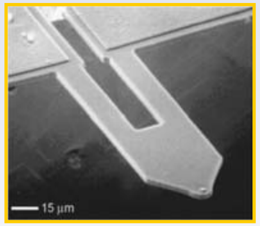
The nanomechanical cantilever:



Lang – Nanotechnology - 2002

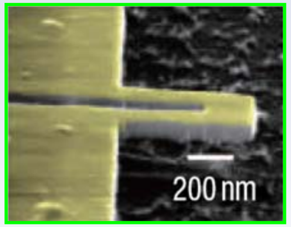
From MEMS to Quasi 1D NEMS

MEMS



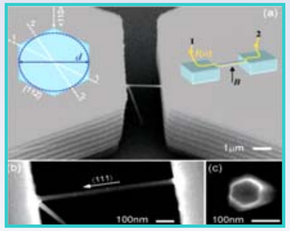
Commecially available piezoresistive MEMS for sensing applications

NEMS



State-of-the-art piezoresistive NEMS
Mo Li et al, Nat. Nanotech. 2, 114 (2007)

SCNW & CNT NEMS



Si NW prototype NEMS resonator
Feng et al, Nano Lett. 7, 1953 (2007)

- Enhanced performace
- Novel functionalities
- New basic properties

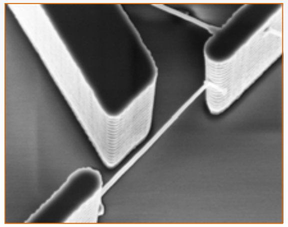
- Highest structural quality to size ratio
- Self-assembled bottom-up fab.
- Unique electromechanical properties

Bottom-up versus top-down nanofabrication

We have explored two different fabrication approaches:

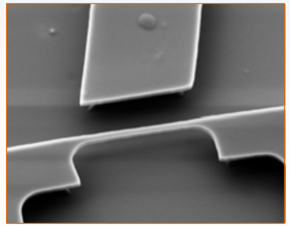
Bottom-up

- Nanowires synthesized using chemical methods

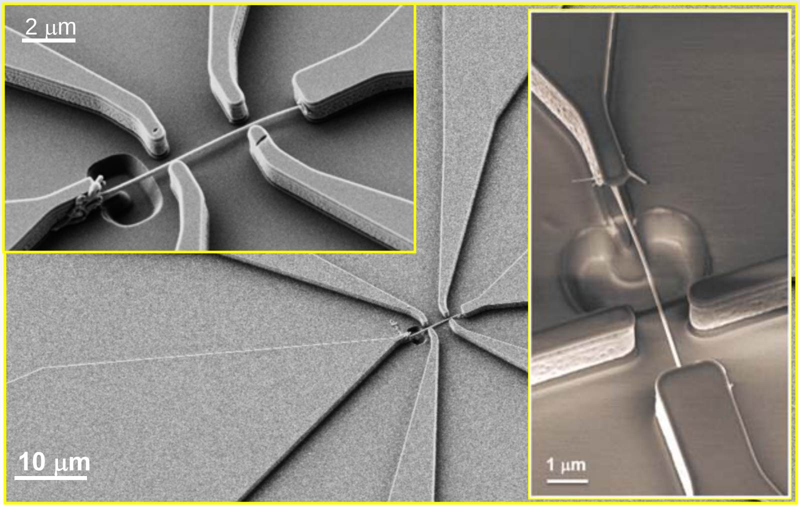


Top-down

- Nanowires defined using photolithography, micromachining methods and oxidation

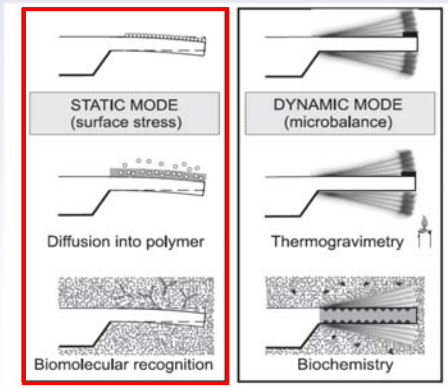


Bottom-up Fabrication Process: Selective deposition of Au Colloids



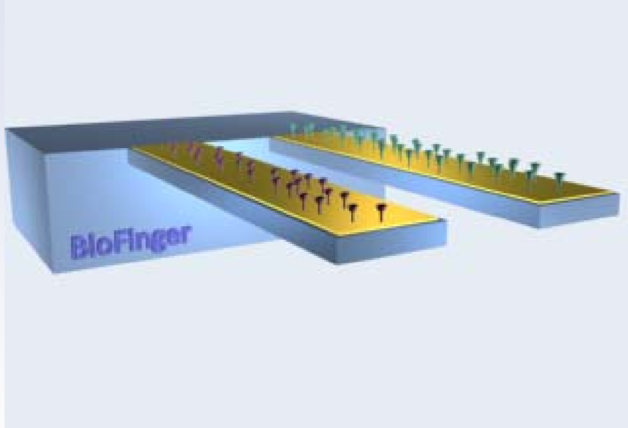
Static versus dynamic mode

The nanomechanical cantilever:



Lang – Nanotechnology - 2002

Example



Dr, Guillermo Villanueva, EPFL

Surface Stress

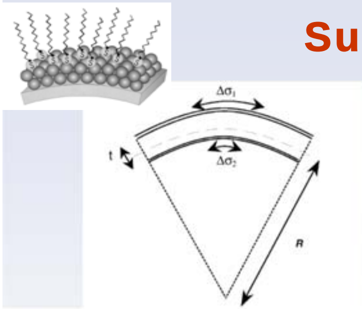


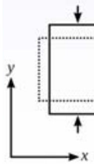
Fig. 3. Lateral view of a thin beam of thickness t subjected to compressive surface stress changes $\Delta\sigma_1$ and $\Delta\sigma_2$. The beam bends around a neutral plane with a constant radius of curvature R.

$$-EI\frac{1}{R}=M=\frac{w\cdot t}{2}(\delta\sigma_1-\delta\sigma_2)$$

$$E\rightarrow E/(1-\nu) \qquad I=\frac{w\cdot t^3}{12}$$

$$\frac{1}{R}=6\left(\frac{1-\upsilon}{Et^2}\right)(\Delta\sigma_1-\Delta\sigma_2)$$

$$\boxed{\Delta z\cong\frac{3(1-\upsilon)L^2}{Et^2}(\Delta\sigma_1-\Delta\sigma_2)}$$



Assuming that the material is compressed along the axial direction:

$$\nu=-\frac{\varepsilon_{\mathrm{trans}}}{\varepsilon_{\mathrm{axial}}}=-\frac{\varepsilon_{\mathrm{x}}}{\varepsilon_{\mathrm{y}}}$$

Poisson's ratio

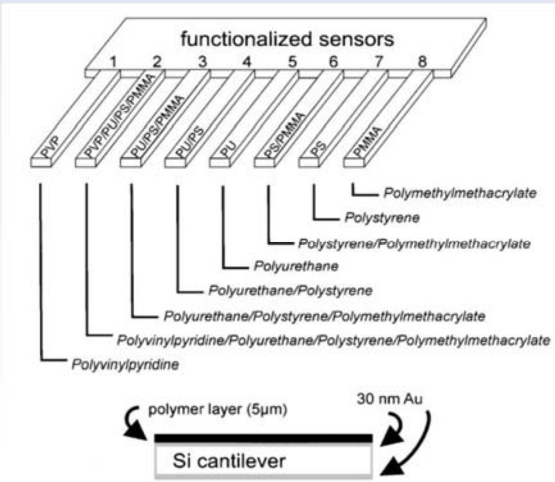
where

v is the resulting Poisson's ratio,

$\varepsilon_{\mathrm{trans}}$ is transverse strain (negative for axial tension, positive for axial compression)

$\varepsilon_{\mathrm{axial}}$ is axial strain (positive for axial tension, negative for axial compression).

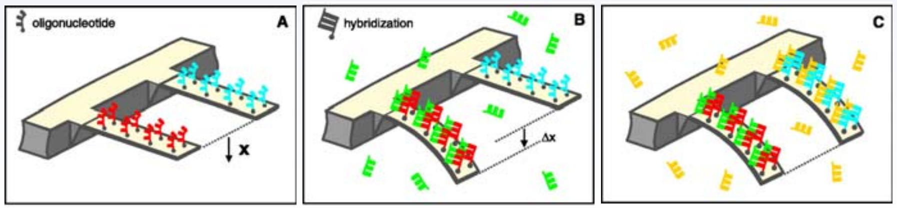
Applications



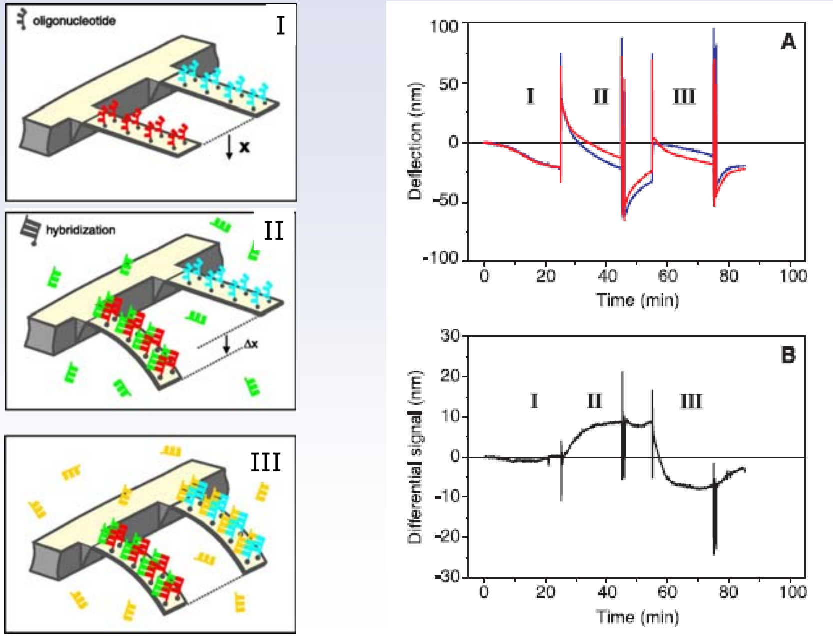
Cantilever sensor array with polymer coatings
Baller – Ultramicroscopy - 2000

DNA Hibridization detection

- Basic idea:
  - → **Coat** each cantilever specifically to each protein / ssDNA
  - → Expose to different analytes and observe bendings → **specific bindings**
  - → **Differential** measurement to have reliable responses



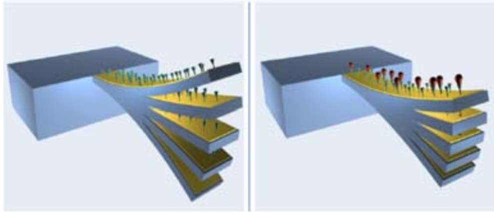
Fritz – Science - 2000

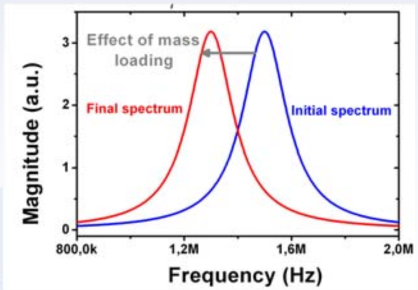


Fritz – Science - 2000

Nanomechanical devices as mass sensors

- **Nanomechanical resonators** allows to measure ultra-small amounts of mass. In comparison to quartz crystal microbalances, they present advantages in terms of mass sensitivity, spatial resolution and system integration
- **Principle of operation**
  - Deposition of mass on top of the nanoresonator
  - Detection of the negative shift of resonance frequency

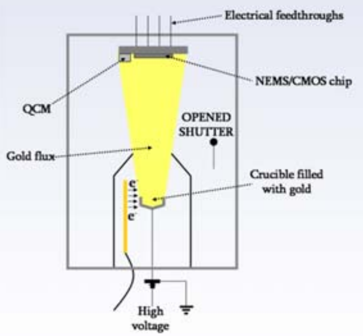


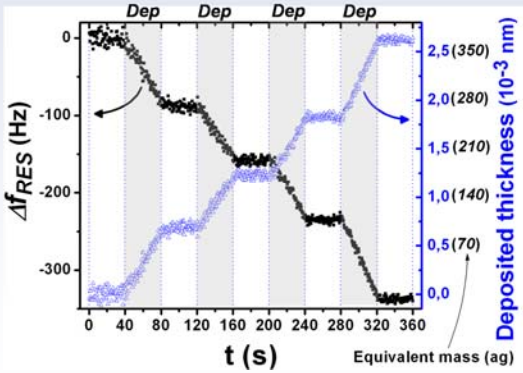


m ➡ fres

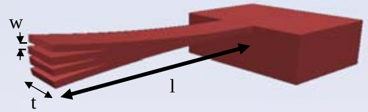
m+δm ➡ fres-δf

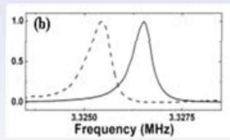
In-situ monitoring of the deposition of ultra-thin gold layers





J. Arcamone et al., Nanotechnology (2008),





$$f_n - \Delta f_n = \frac{1}{2\pi}\sqrt{\frac{k}{\Delta m + m_{eff}}}$$

$$k = \frac{E}{4}\cdot\frac{w^3\cdot t}{l^3} \quad \text{(N/m)}$$

$$f_o = \frac{1}{2\pi}\sqrt{\frac{E}{\rho}}\frac{w}{l^2}$$

$$\frac{\delta m}{\delta f} = 50.7\frac{k}{f_o^3} \approx 0.83\cdot 10^3 l^3 t$$

$$\boxed{S_m = \frac{\Delta m}{\Delta f_n} \approx -\frac{2m_{eff}}{f_n}}$$

Sensitivity

$$\boxed{R_m = \frac{\Delta f_n}{\Delta m} \approx -\frac{f_n}{2m_{eff}}}$$

Responsitivity

Cantilever	l (μm)	t (μm)	w (μm)	k (N/m)	f_o	m_{eff} (g)	Sensitivity (g/Hz)
Soft	450	50	2	0.2	14 kHz	$2.5\cdot10^{-8}$	$3.8\cdot10^{-12}$
Stiff	125	30	4	44	364 kHz	$8.4\cdot10^{-9}$	$4.9\cdot10^{-14}$
Nano	10	0.5	0.1	0.02	1.4 MHz	$2.8\cdot10^{-13}$	$4.2\cdot10^{-19}$
Nano	1	0.5	0.1	20	134 MHz	$2.8\cdot10^{-14}$	$4.2\cdot10^{-22}$

Which is the minimum detectable mass ?

Sensitivity $$\frac{\delta m}{\delta f} = 50.7\frac{k}{f_o^3} \approx 0.83 \cdot 10^3 l^3 w \,(\text{gr/Hz})$$

Resolution $$\delta m = S \cdot \delta f \longrightarrow$$ (minimum detectable change of frequency)

Noise limits the minimum detectable change of frequency

<u>Nanomechanical resonator (mechanical noise)</u>

- ✓ Thermomechanical fluctuation
- Temperature fluctuations
- Absorption / desorbtion processes

$$\delta\omega_o \approx \sqrt{\frac{k_B T}{E_C}\frac{\omega_o BW}{Q}}$$

<u>Electrical circuit (Electrical noise)</u>

$$\delta\omega_o \approx \frac{BW}{SNR}$$

Minimum detectable mass assuming only mechanical noise

$$\delta m \approx 2 m_{eff}\left(\frac{BW}{Q\omega_o}\right)^{1/2} 10^{(-DR/20)}$$

$$DR(dB) = 10\log\left(E_c / k_B T\right)$$

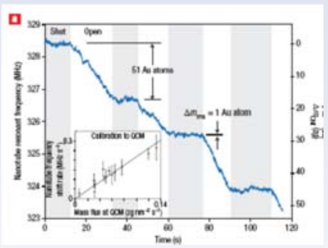
$$E_c = m_{eff}\,\omega_o^2 \left\langle x_c^2 \right\rangle$$

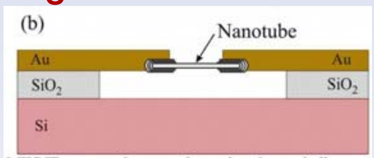
$$BW < \frac{\omega_o}{2\pi Q}$$

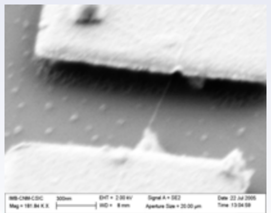
T=300 K		f_o	δf	M_{eff} (g)	ΔM (g)
t=100nm, l=10μm, w=600nm	Q=20	1.4 MHz	<10 kHz	$2.8 \cdot 10^{-13}$	$7.72\ 10^{-18}$
	Q=10000		<10 Hz		$1.54\ 10^{-20}$

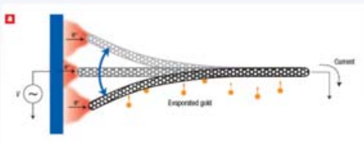
Attogram sensitivity is achievable with sub-micrometer size cantilevers
Zeptogram sensitivity is achievable with nanometer size cantilevers

1 atom mass sensitivity using carbon nanotubes

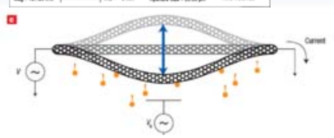








Jensen, Kim and Zettel, Nature Nanotechnology (2008)



A. Bachtold et al. Nanoletters (2009)

Summary nanomechanical sensing

Concept

- Improve **sensitivity** by decreasing the dimensions
- **Selective bending** of the cantilever allowing entity recognition and measurement

Advantages:

- **No labeling** needed for detection
- Easy and "cheap" production (Si technology)
- Can operate in air, vacuum, or liquid **environments**
- **Fast analysis** (within some minutes)
- **Cyclic operations** after purging
- Arrays :
  - **Differential** as well as **simultaneous** measurements
  - Individual coating of each cantilever allows measurement of **multiple substances within a mixtures**

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Julien Arcamone
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Iñigo Martin
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