Nanotechnology and Material Science

Lecture VIII

Department of Physics, BME

2024.

Top Down & Bottom Up Approaches

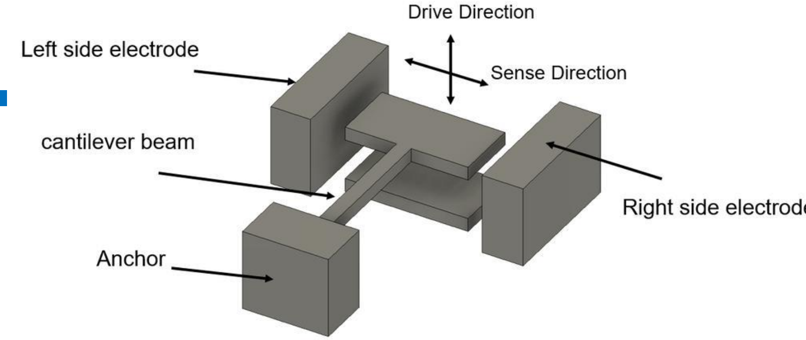
Onsite course, BMETE11MF58

website: http://physics.bme.hu/BMETE11MF58_kov?language=en

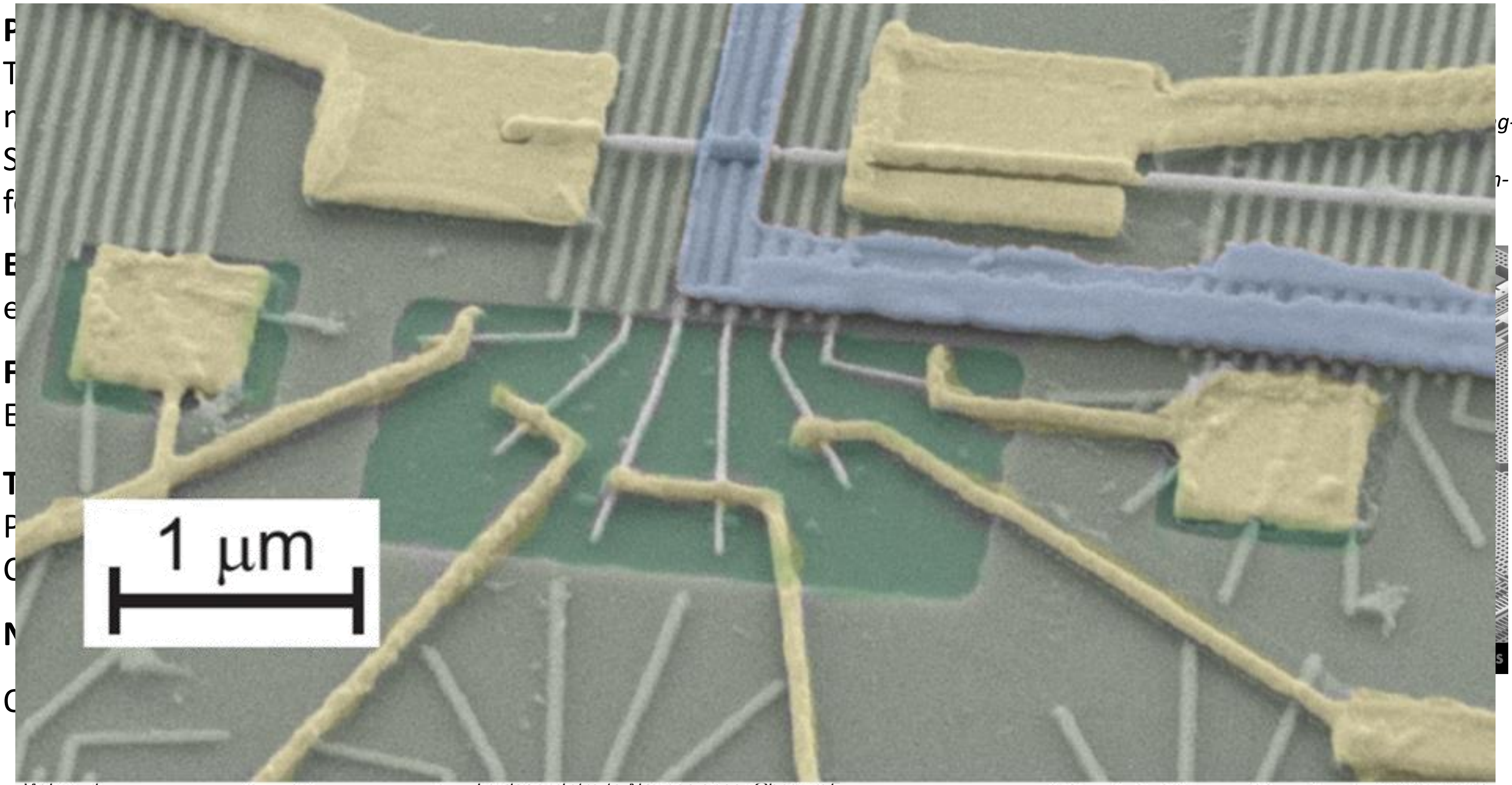
Microsoft Teams, BME: Nanotech and Mat. Science

Email: Szabolcs Csonka csonka.szabolcs@ttk.bme.hu

Top down techniques



„Top down means proceeding to build like a sculptor, chipping away at a block of marble to produce a statue. ”
Typical example: MEMS systems (see talk of P. Fürjes, MFA)

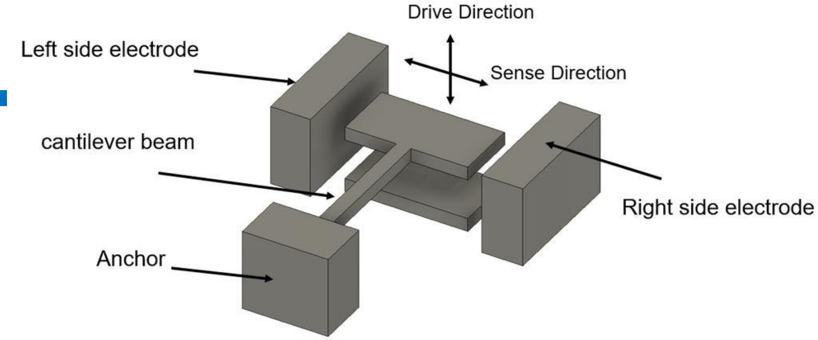


Wikipedia

Lindsay : Intro to Nanoscience, Chapter 5

Top down techniques

„Top down means proceeding to build like a sculptor, chipping away at a block of marble to produce a statue. ”
Typical example: MEMS systems (see talk of P. Fürjes, MFA)



(Up)Principle structure of a MEMS gyroscope
(Down) State-of-the-art gyroscope MEMS sensor L3G4200D
http://www.memsjournal.com/2011/01/motion-sensing-in-the-iphone-4-mems-gyroscope.html
https://hobbydocbox.com/Radio/73640526-Fabrication-testing-and-characterization-of-mems-gyroscope.html

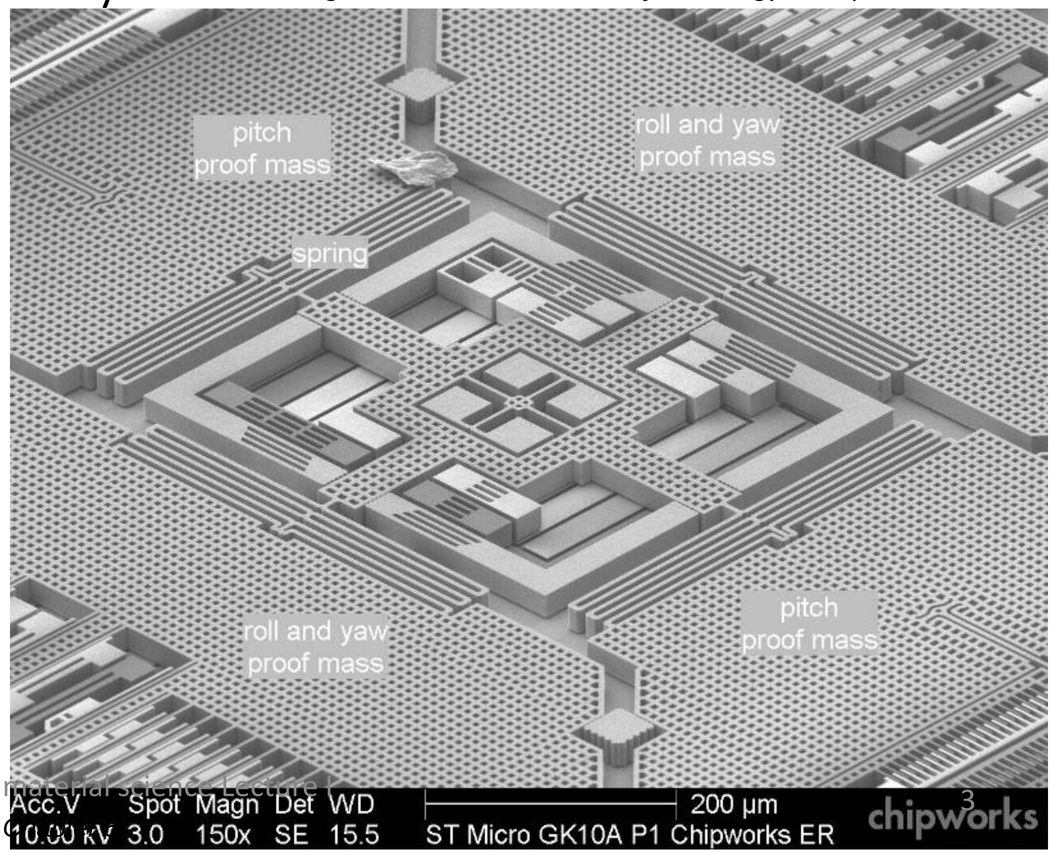
Photolitography
Typical first step to make nanostructures. Interfacing macro to micro. Diffraction limit of lenses 0.5um.
Still devices with 10nm resolution is also accessable. Only in a few semiconductor fabs. (see intro talks)

EBL (Electron beam lithography)
exposes lithography resists with very fine e-beam

FIB (Focused Ion Beam), HIB (Helium ion beam)
Etch materials directly by bombarding them with energetic ions

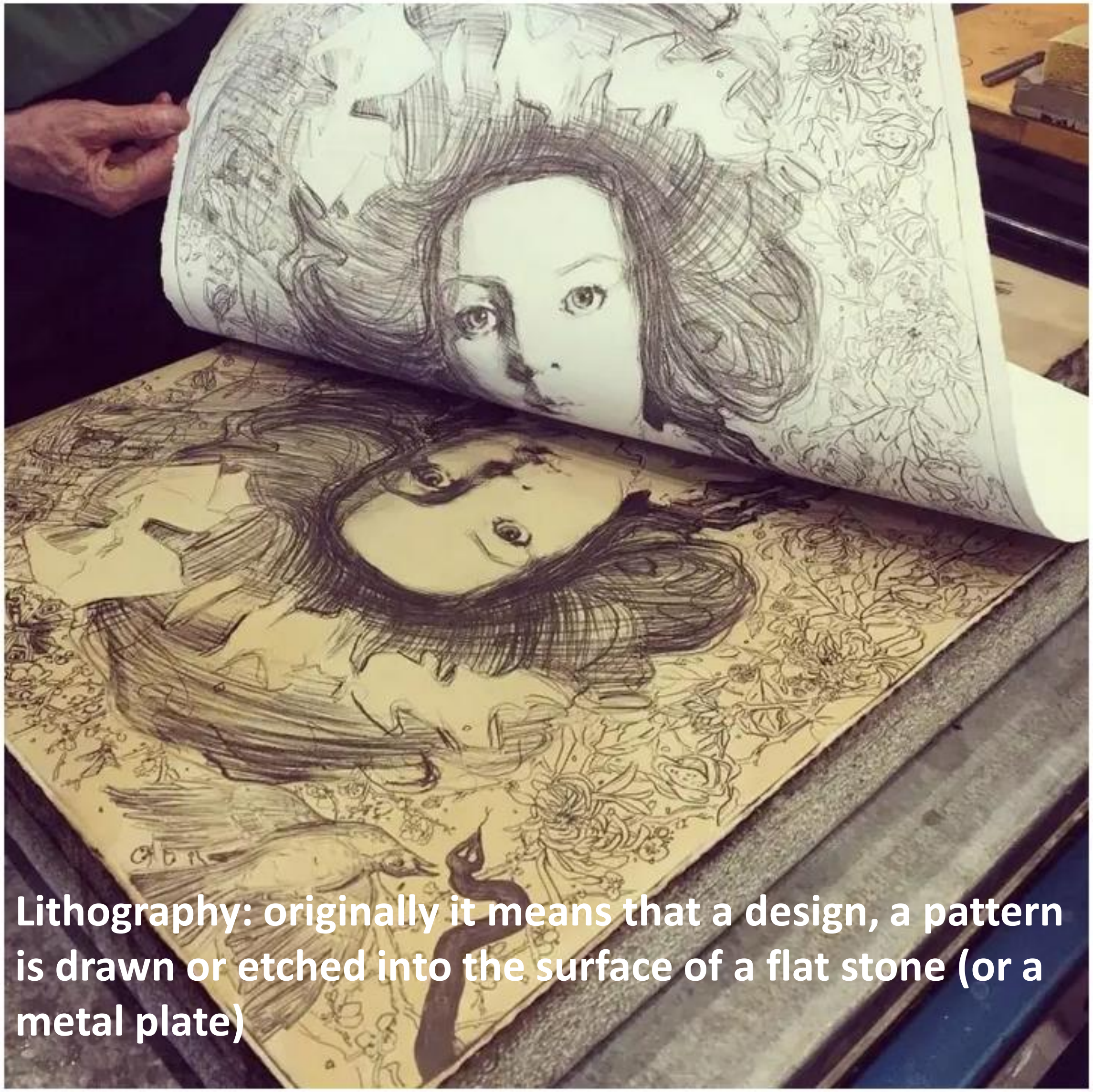
Thin film technologies
PVD: evaportion, e-beam, sputtering, MBE
CVD

Nanoimprint lithography
Others .. STM, AFM lithography, …



Wikipedia
Lindsay : Intro to Nanoscience, O

Lithography



https://avidipta.art/a-brief-history-of-lithography/

Photolithography

Toolkit of semiconductor fabrication plant

Steps: oxidation, masking, implantation, Etching, Metallization, Lift-off **in localized areas**.

How do we define the areas?

Coat wafer with polymer "resist", 100-2000nm thick

When exposed to light:

- Negative-type resist: light cross-links the resist → insoluble
- Positive-type resist: light induces breaks, scission of chains (e.g. PMMA) → more soluble

With an optical setup the light **is illuminated through a mask** containing the pattern and projected to the resist with ¼ reduction (exposure)

Remove (un)exposed areas of pos. (neg.) resist with a solvent (development) → resist mask for any step (see top), then remove the resist with another solvent.

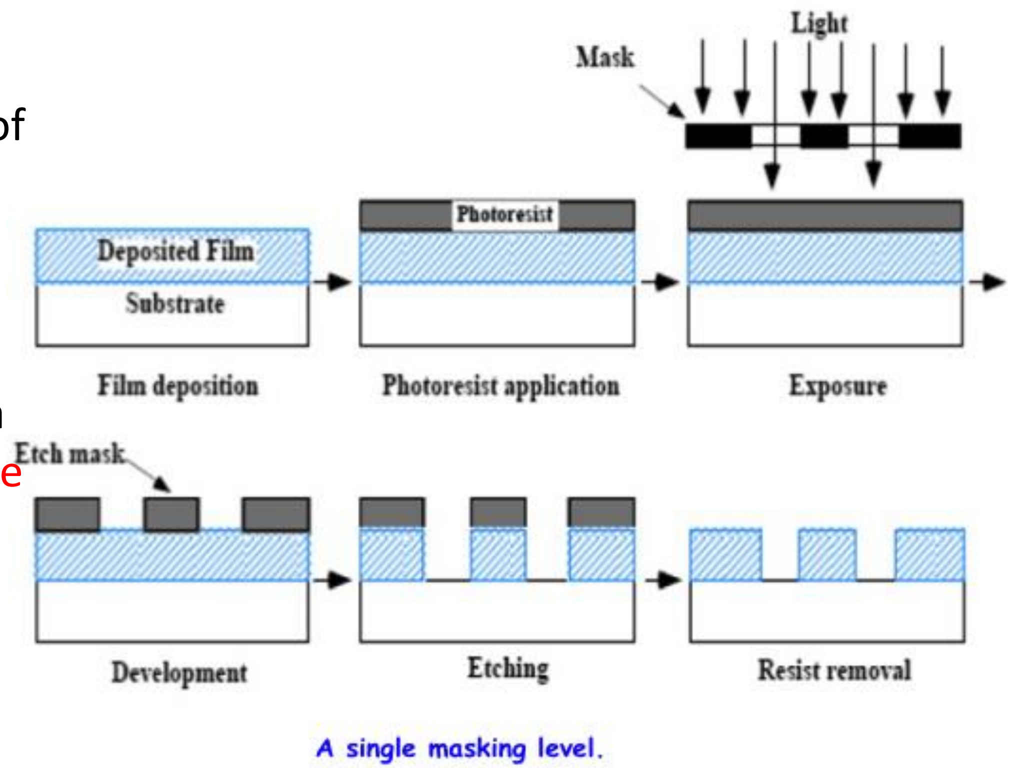
Diffraction limit of the smallest structures:

$$r = \frac{k\lambda}{NA}$$

k=0.5-1, NA numerical aperture of the projector lens.

Resolution in semiconductor industry 10nm

Excimer lasers are used: deep UV λ<200nm, high light intensity.



Example: etching a deposited film using a positive resist

https://lnf-wiki.eecs.umich.edu/wiki/Lithography

Wikipedia *Lindsay : Intro to Nanoscience, Chapter 5* *see more detail in Gabor Kiss: Micro and Nanotechnology*

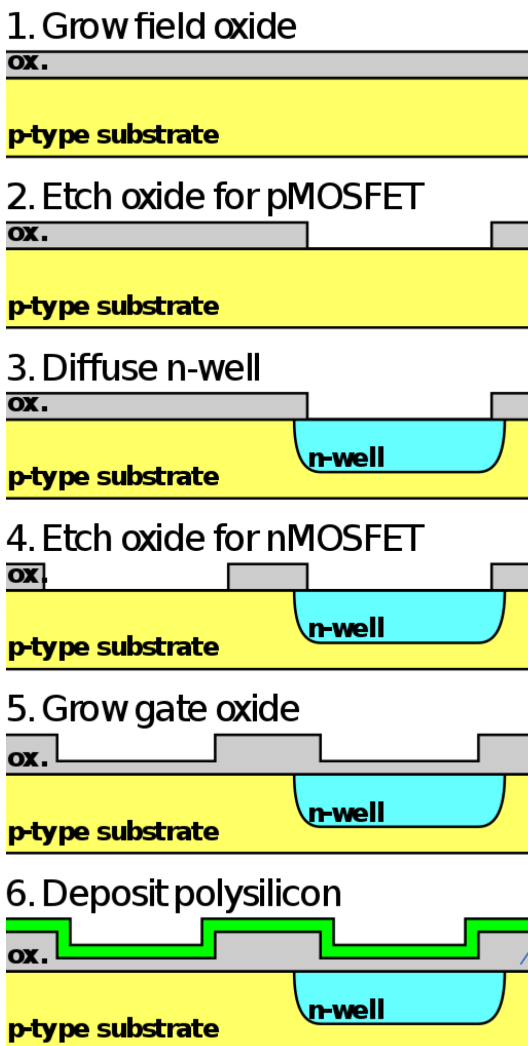
Photolithography

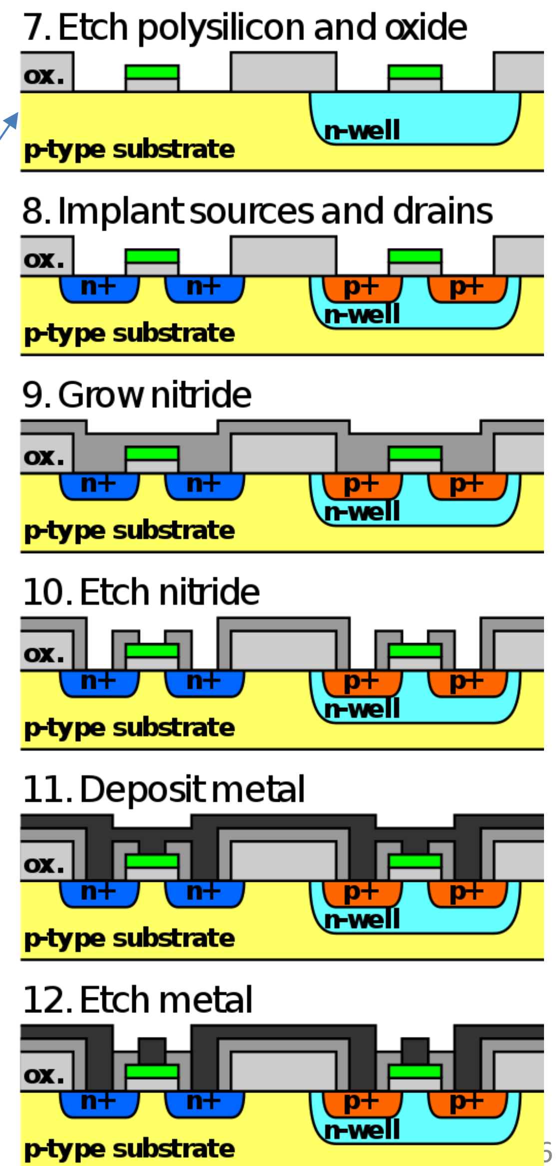
Toolkit of semiconductor fabrication plant

(Up) Wikipedia

Steps: oxidation, masking, implantation, Etching, Metallization, Lift-off **in localized areas.**

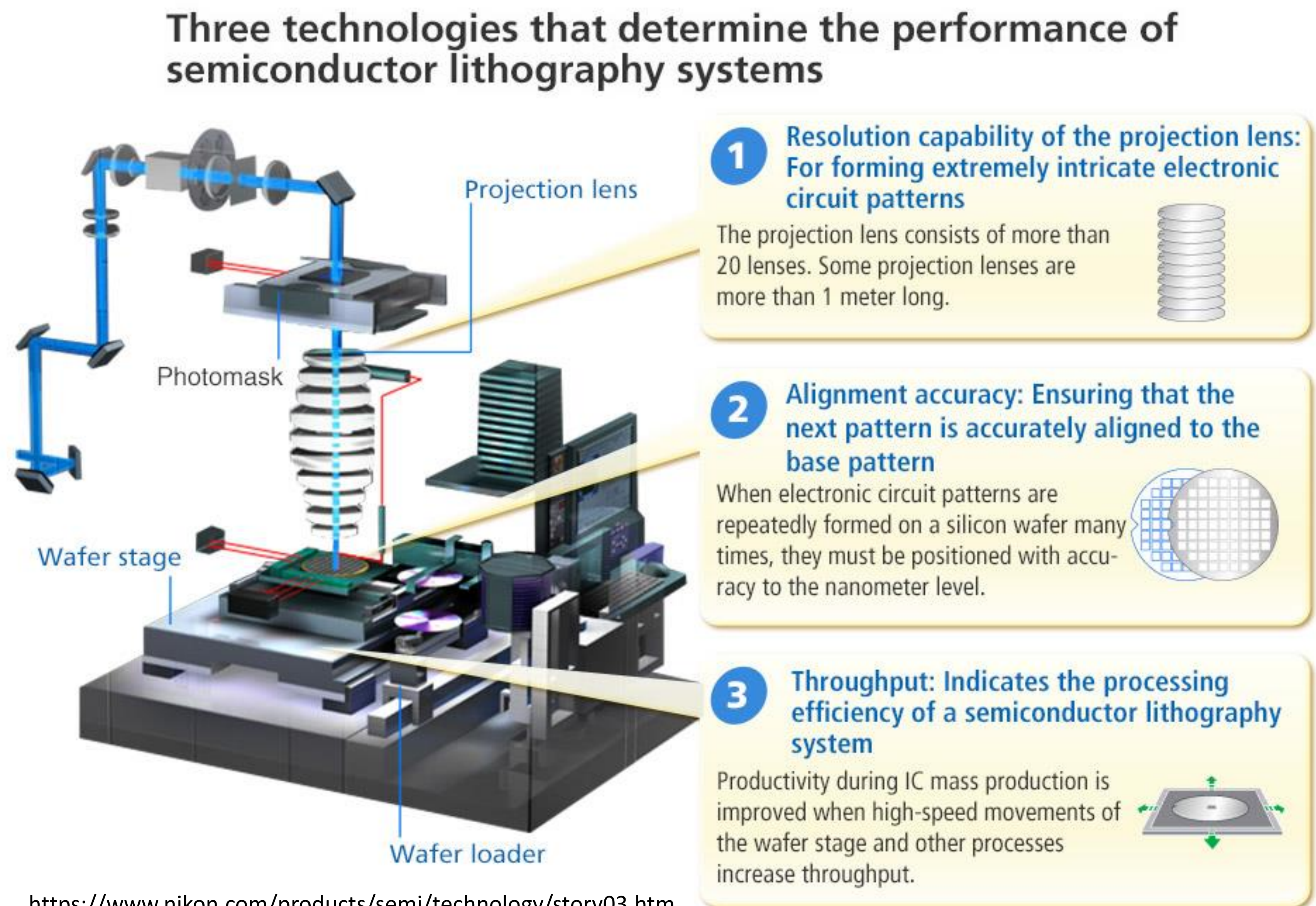
Example: MOSFET (pnp and npn transistor pair)





Wikipedia *Lindsay : Intro to Nanoscience, Chapter 5* *see more detail in Gabor Kiss: Micro and Nanotechnology*

Photolithography



https://www.nikon.com/products/semi/technology/story03.htm

Extreme Ultraviolet Lithography

Principle:

UV light with λ=13.5nm used for exposing.

Excimer laser is used to excite tin or xenon plasma. Not a coherent source.

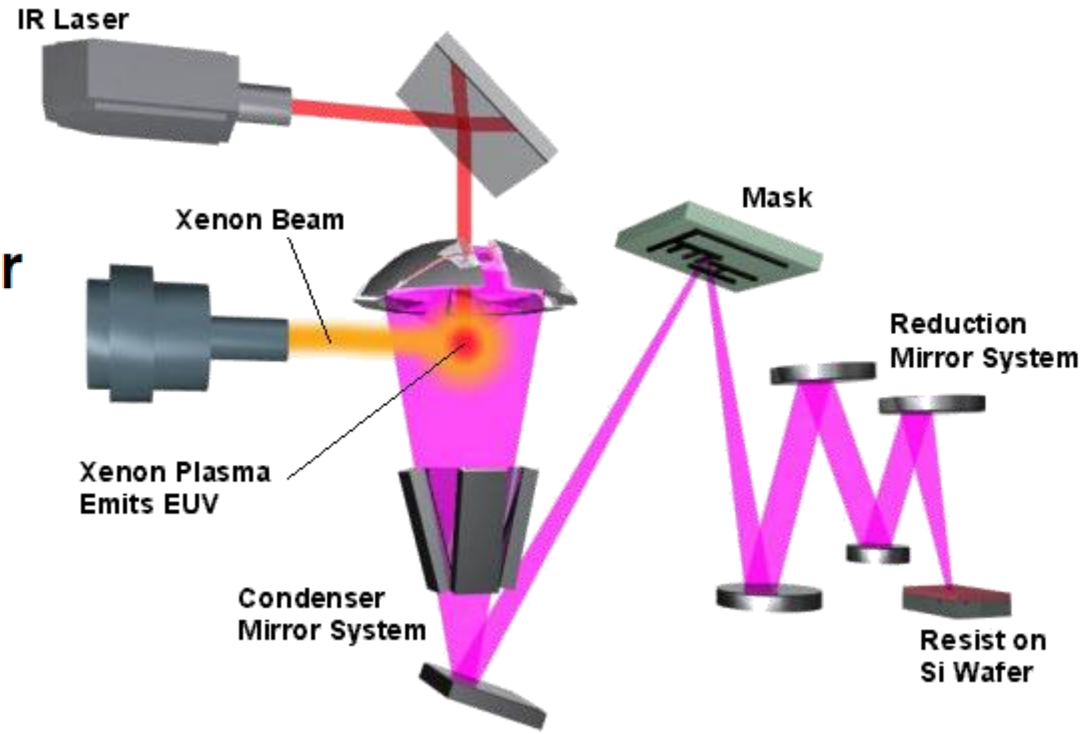
Challenges: make optics, create dust free environment.

Optics: No material is transparent for this λ! → no lenses

optical system is built out of mirrors; also difficult to make, they exploit constructive interference in multiple layers of materials (~13 nm thick each → expensive)

4x reduction system as for optical lithography

Wikipedia, http://barrett-group.mcgill.ca/tutorials/nanotechnology/nano05.htm



Feature | Semiconductors | Nanotechnology

5 Jan 2018 | 16:00 GMT

EUV Lithography Finally Ready for Chip Manufacturing

TSMC, Intel and Samsung will use for the next generation of 7nm node.

Resolution of 13nm with ASML Twinscan NXE3400B (2018)

Wikipedia *Lindsay : Intro to Nanoscience, Chapter 5*

Electron beam lithography

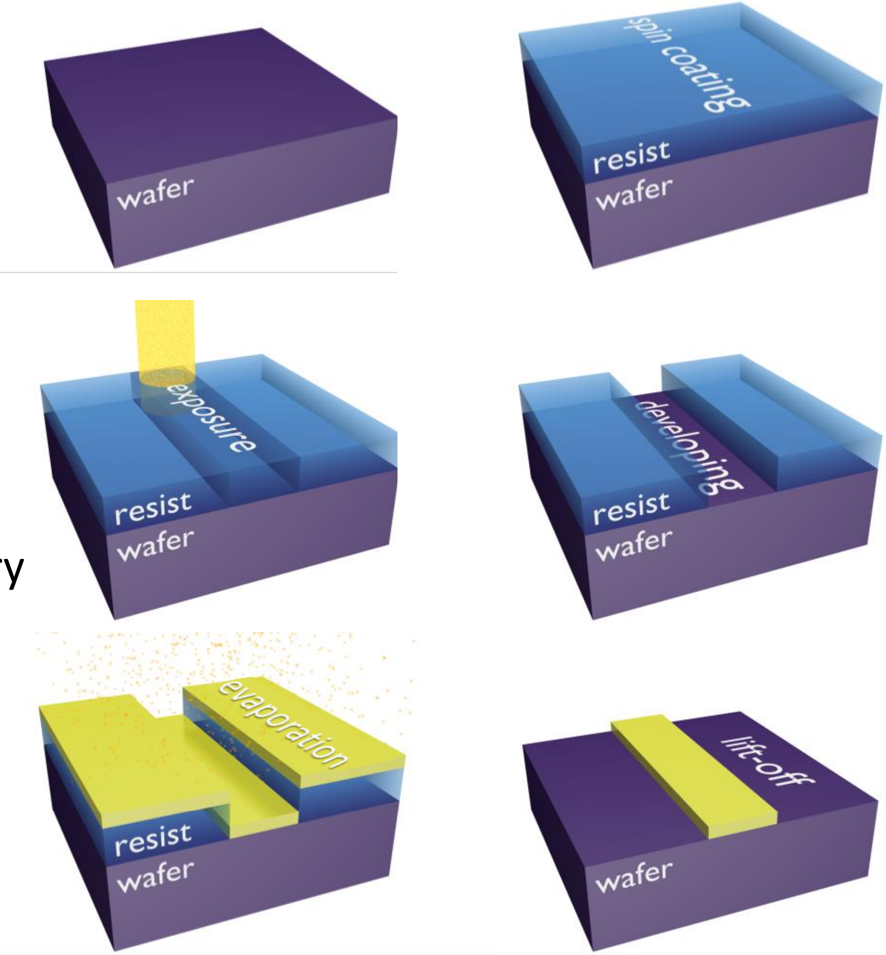
Spot size of SEM: few nm in a large field of view
E-beam used to scission a resist like PMMA
EBL is a SEM with a fast beam-blanking feature

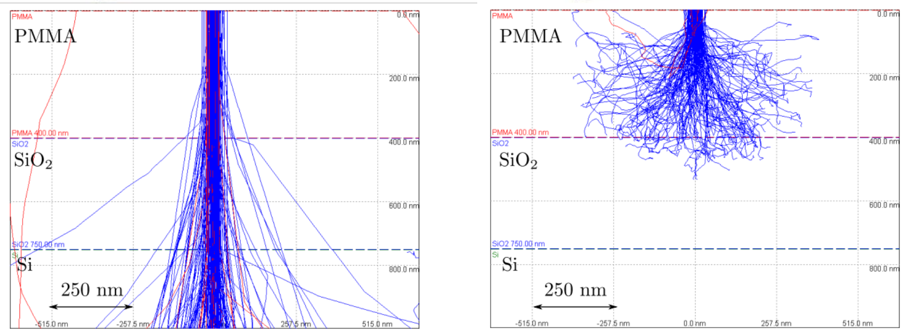
Typical process: metallization, see figure.

Resolution:
not limited by spot size, but by proximity effect. Secondary electrons generated by e-beam in the sample and the backscattered ones further expose the resist.
E.g. 20kV secondary electrons reach a circle of ~2µm.

Typical resolution is <100nm, 10nm is achievable.

Issue: sequential, throughput is small.
But for research or writing a mask for use in mass production it is the perfect tool.





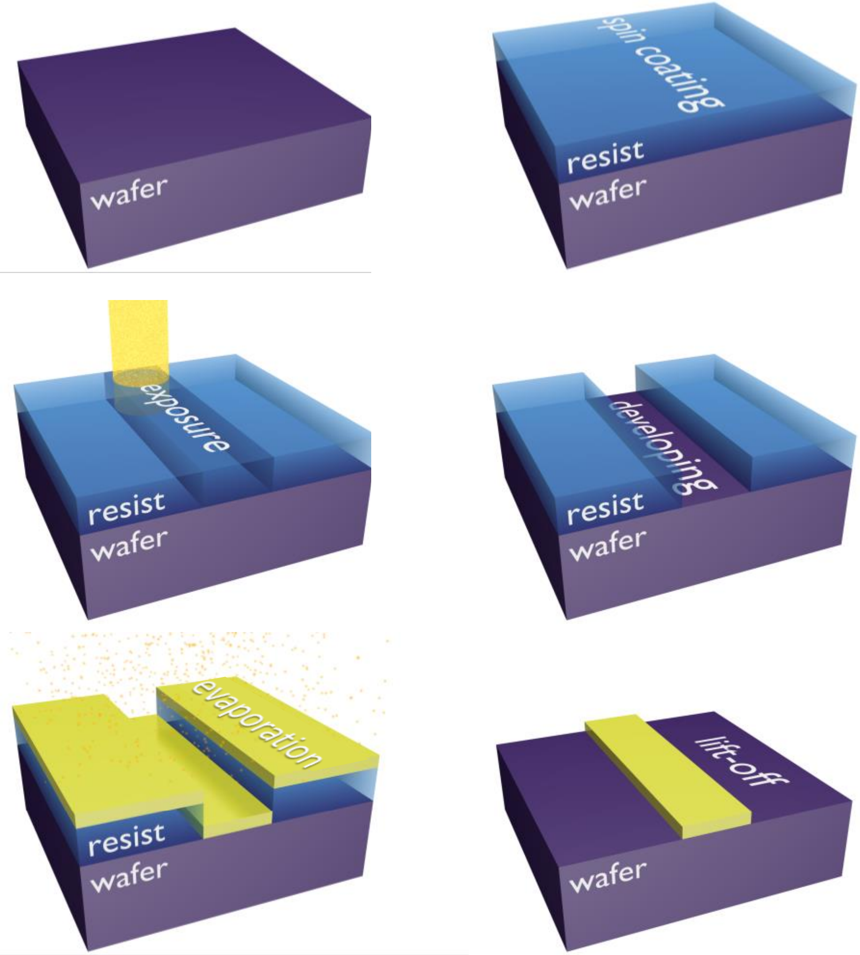
a) b)

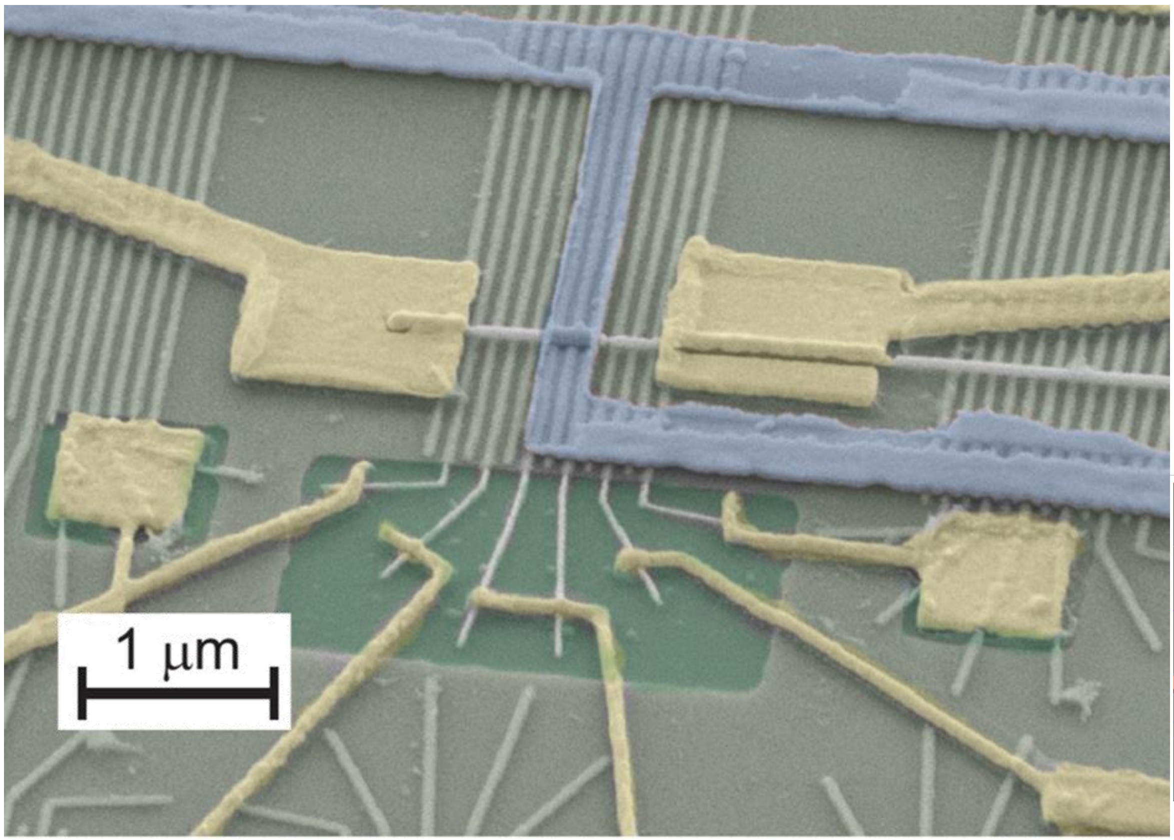
Wikipedia *Lindsay : Intro to Nanoscience, Chapter 5* *see more detail in Gabor Kiss: Micro and Nanotechnology*

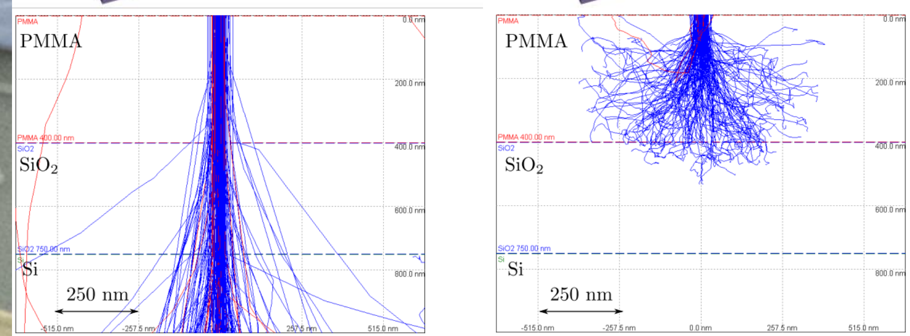
Electron beam lithography

Spot size of SEM: few nm in a large field of view
E-beam used to scission a resist like PMMA
EBL is a SEM with a fast beam-blanking feature

Typical process: metallization, see figure.







a) b)

Wikipedia *Lindsay : Intro to Nanoscience, Chapter 5* *see more detail in Gabor Kiss: Micro and Nanotechnology*

Thin film technologies

Widely used techniques: evaporation, sputtering, etc.
High and ultra high vacuum systems are required!

Consider: number of molecules striking the surface per area and unit time (N_S):

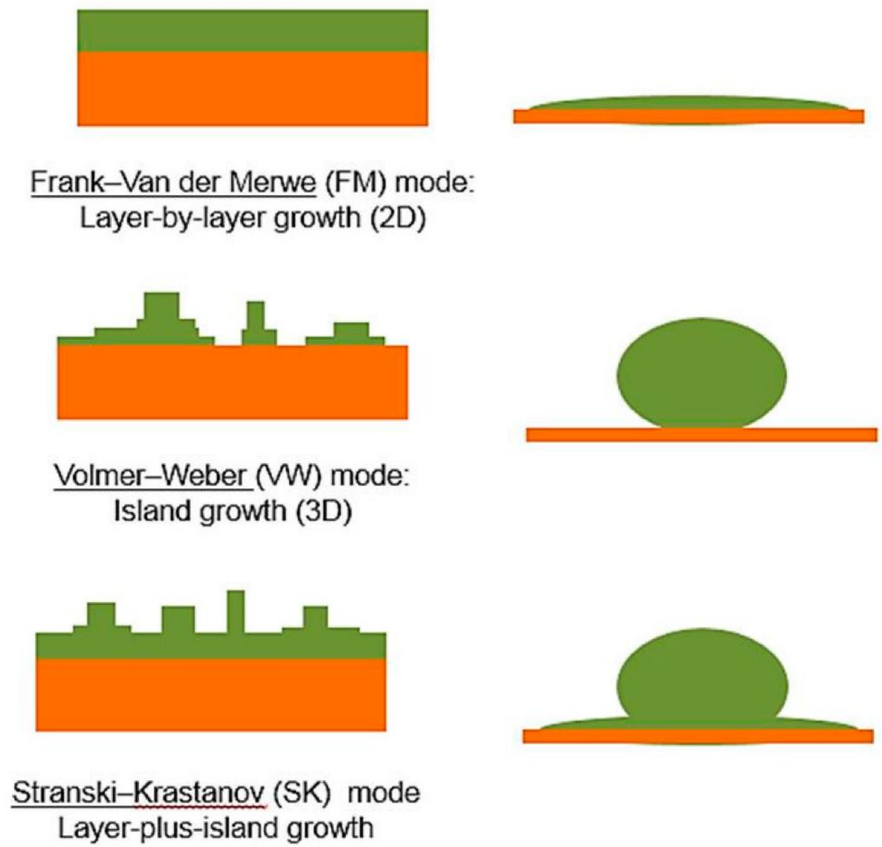
$$N_s = \frac{1}{2\sqrt{3}}\rho\sqrt{\langle v^2\rangle}, \qquad \rho = N/V = P/k_B T$$

The kinetic energy using $\frac{1}{2}mv_x^2 = \frac{1}{2}k_B T$:

$$\sqrt{\langle v^2\rangle} = 1.58 \times 10^4 \sqrt{\frac{T}{M}}\ \mathrm{cm/s}$$

where M is the mass of the molecule in atomic mass and T is the temperature in K, p is the pressure.
E.g. for oxygen at room temperature at $p=10^{-6}$ mbar:
N_S= 1 monolayer/sec.
→ For fine structures 10^{-9} mbar is a min. requirement.

Different modes of crystal growth on surface.
Typically outcome is polycrystalline.
Growth of epitaxial layers requires special conditions.



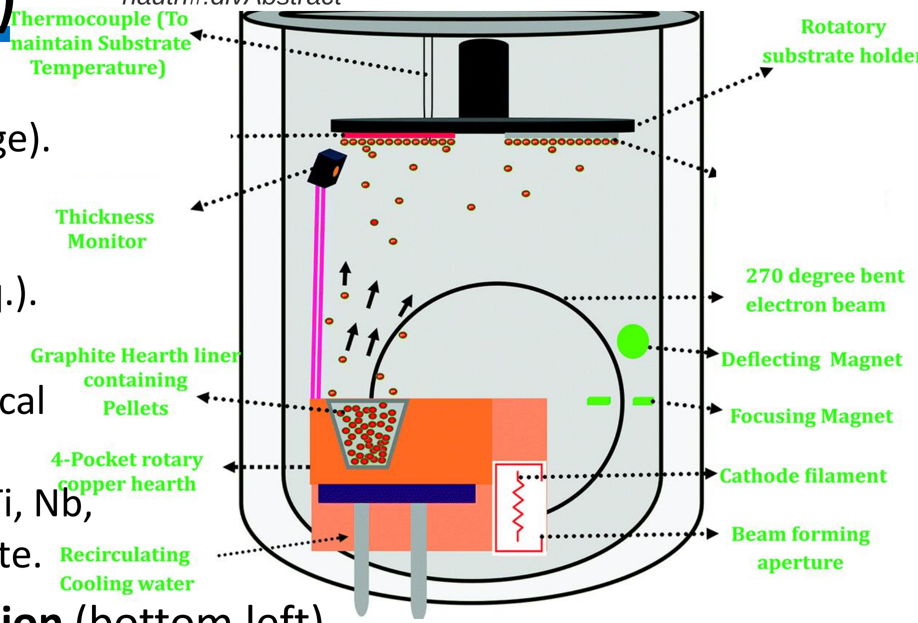
Depending on interface and bulk energy balances, temperature, deposition rate, and energy of arriving atoms, different modes of crystal growth could take place. Three main modes are shown at atomic level (left) and bulk level (right).

https://www.mdpi.com/2073-4352/7/6/178

Lindsay : Intro to Nanoscience, Chapter 5 *see more detail in Gabor Kiss: Micro and Nanotechnology*

Physical Vapour Deposition (PVD)

Electron beam deposition system
https://pubs.rsc.org/en/content/articlelanding/2016/an/c6an00922k/unauth#!divAbstract



Thermal evaporation

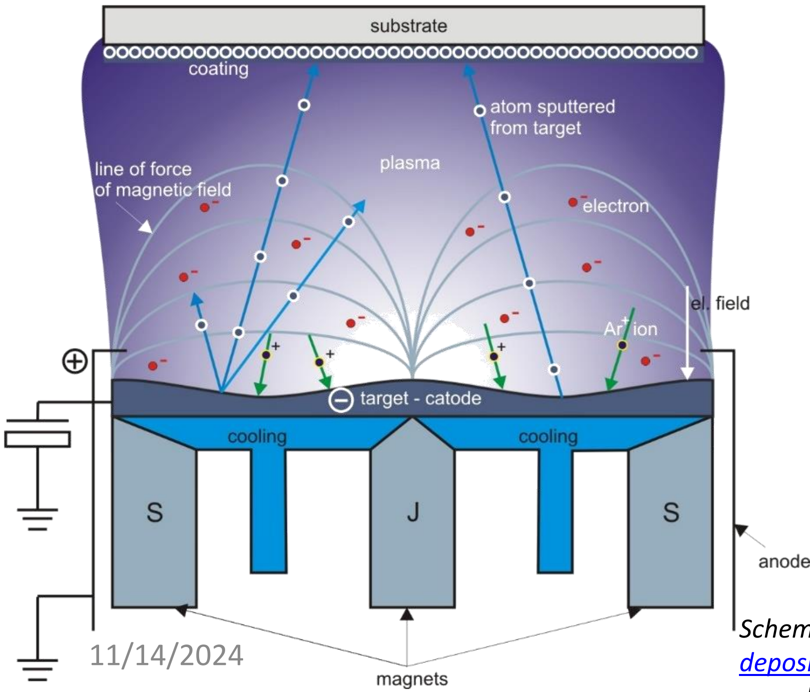
Metal is placed in a tungsten boat and heated electrically (no image).
Sample is clamped to a stage at a distance from the target.
Atoms condense on all surfaces (also with e-beam)
Quartz crystal monitor is used (lab course on piezo resonance freq.).

Electron-beam deposition (top right)

Energetic e-beam is focused on the metal target, which induces local heating → evaporation/sublimation
Pros: it allows evaporating refractory metals (high melting point: Ti, Nb, W, Mo…); no contamination from the boat; wide range of evap. rate.
Cons: risk of X-ray damage, expensive

Sputter deposition (bottom left)

Energetic ions are used to bombard the surface of the target. Typically Ar (O, N) atoms are ionized by electrons, creating a plasma. Ar ions are accelerated by voltage towards the target, and target atoms kicked out and scattered towards the substrate.
Magnetron sputtering systems use magnets to trap free e's close to the target and ionize Ar there. → Higher sputtering rate, low e flux on substrate.
Pros: easier to control composition (e.g. co-sputtering, NbN); step coverage is better (more diffusive gas; e-beam is nearly ballistic)
Cons: High energy target atoms; non-directional (diffusive)
E-beam v.s. sputter deposition depends on particular applications.



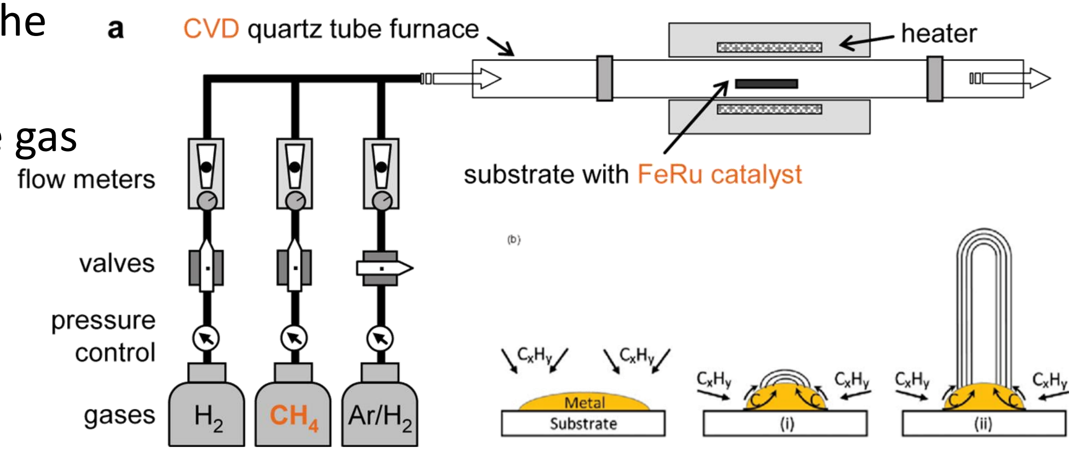
Schematic structure of a magnetron sputtering system. http://www.umms.sav.sk/6493-en/physical-vapor-deposition/, http://www.ajaint.com/what-is-sputtering.html
Lindsay : Intro to Nanoscience, Chapter 5   see more detail in Gabor Kiss: Micro and Nanotechnology

Chemical Vapour Deposition (CVD)

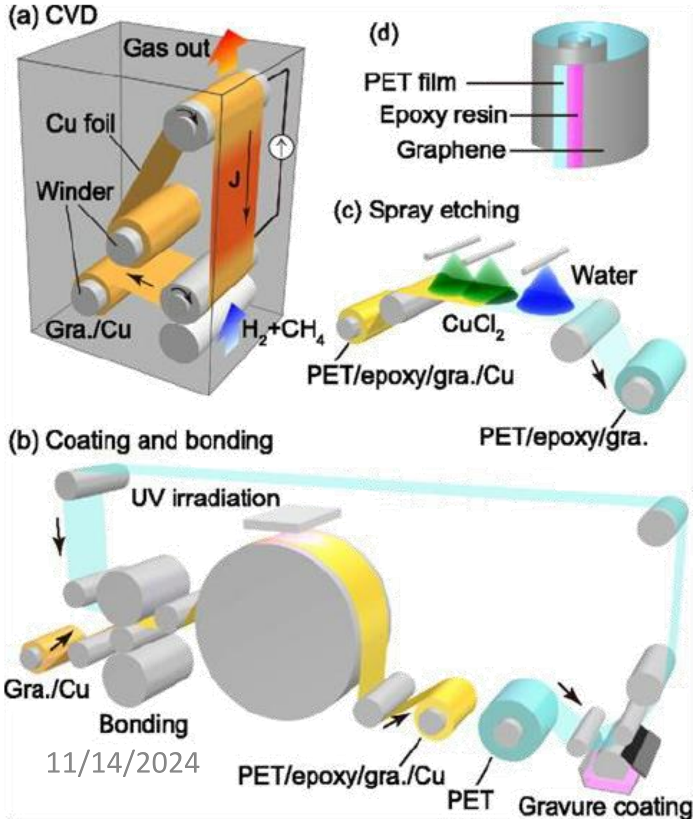
Creation of reactive chemical species close to the surface to be coated
E.g. growth of polycrystaline silicon from silene gas (600C and 1mbar)

$$SiH_4 \rightarrow Si + 2H_2$$

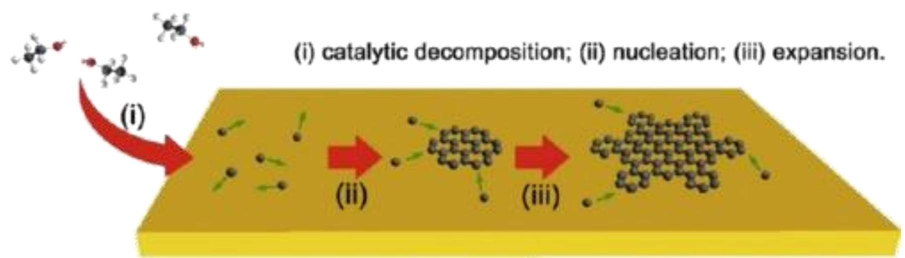
E.g.2: Growth of carbon nanostructures: graphene, nanotube (rather bottom-up)



(Up) Typical CVD system to grow carbon nanostructures. Calayst particles with e.g. CH4 gas creates carbon nanotubes. The schematic growth process is shown bellow.
https://www.nano.physik.uni-muenchen.de/nanophysics/research/rep11.html
https://www.semanticscholar.org/paper/Chemical-vapor-deposition-of-carbon-nanotubes%3A-a-on-Kumar-Ando/8cad65216fe922b14c5c947330cc791341f621fb



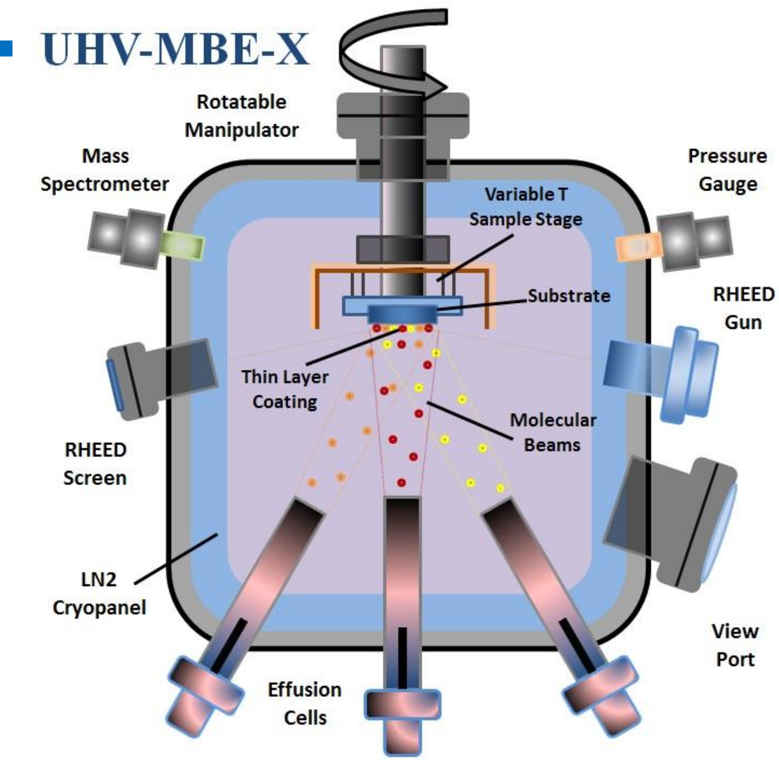
(Down) Basic process of CVD growth of graphene on Cu substrate from CH4.
(Left) Continous roll-to-roll CVD growth and transfer of large area graphene
https://www.sciencedirect.com/science/article/abs/pii/S0379677915300138
https://www.researchgate.net/figure/Schematic-of-continous-roll-to-roll-CVD-growth-and-transfer-of-large-area-graphene_fig5_249286739



Lindsay : Intro to Nanoscience, Chapter 5 *see more detail in Gabor Kiss: Micro and Nanotechnology*

Molecular Beam Epitaxy (MBE)

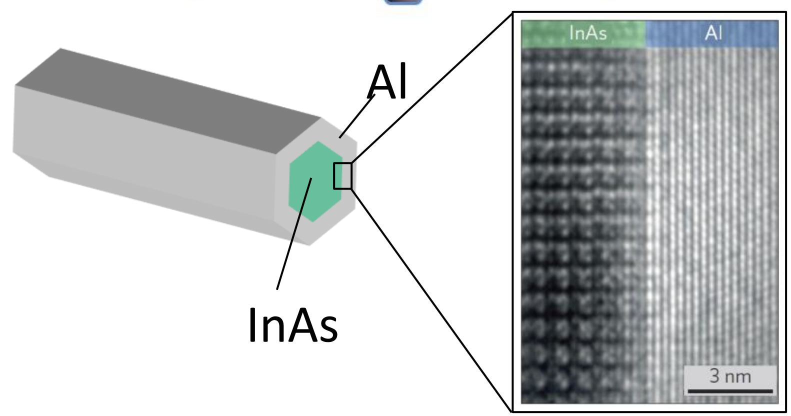
Typical MBE setup http://www.adnano-tek.com/products-ver-1.html



Epitaxialy growth: sequential deposition of crystalline (NOT polycrystalline) layers of specific elements/compounds.
Limited in combination of substrate and growth material: lattice mismatch (see intro).
E.g. GaAs/AlGaAs, Si/SiGe, InAs/AlSb, InGaN/GaN
-> Band gap engineering.
Advanced thermal evaporator system:

- UHV environment.
- Substrate: cleaned, single crystal face
- Atomic beam sources are placed far
- RHEED sensor (Reflection high-energy electron diffraction)
  Monitor thickness by diffracted beam intensity caused by reflections from the interface and surface layers
  Sub-atomic layer-thickness resolution→ follow growth from layer to layer

Frank van Der Merve crystal growth competes with VW and SK growth.
Expensive technique with perfect outcome.
Semiconductor heterostructures are widely used in electronics (GaAs/AlGaAs) and optoelectronics. (GaN – see blue LEDs, InGaN)
Huge impact on applications and also on quantum electronics and quantum optics.

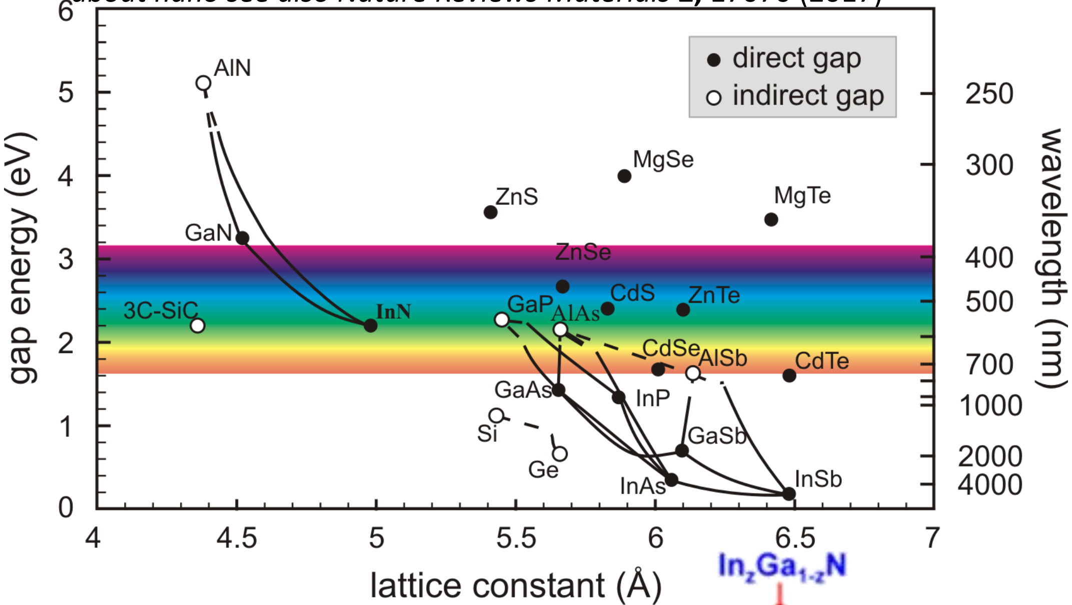


Reflection-free superconductor/semiconductor interface with epitaxial growth of Al on InAs nanowires
P. Krogstrup, Nature Materials 14, 400 (2015)

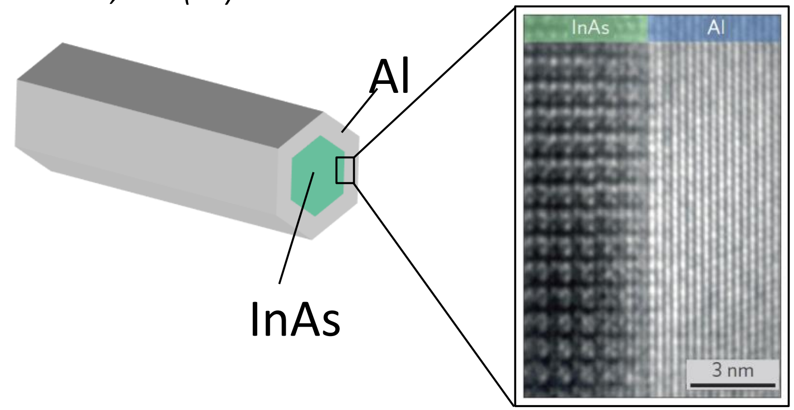
Lindsay : Intro to Nanoscience, Chapter 5 see more detail in Gabor Kiss: Micro and Nanotechnology

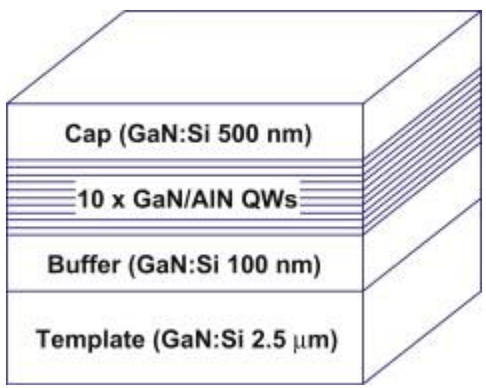
Molecular Beam Epitaxy (MBE)

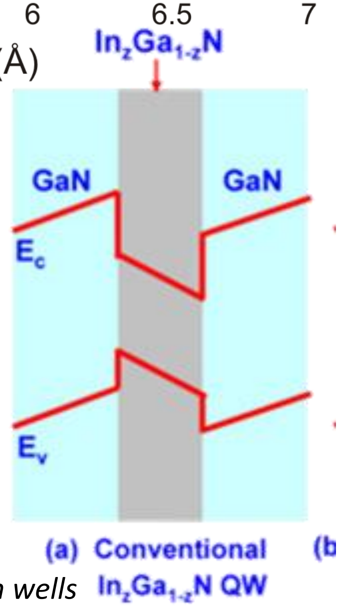
Band gap engineering,
http://gorgia.no-ip.com/phd/html/thesis/phd_html/node4.html
about nano see also Nature Reviews Materials **2,** 17070 (2017)



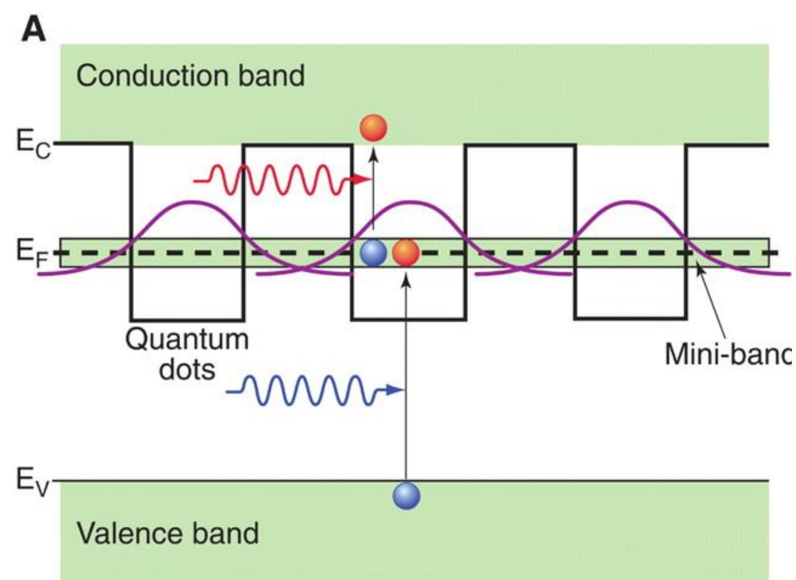
Example of MBE growth: Reflection-free superconductor/ semiconductor interface with epitaxial growth of Al on InAs nanowires P. Krogstrup et al. , Nature Materials 14, 400 (15)







(Up) Example2 of MBE growth: optical quantum wells
https://www.osapublishing.org/oe/abstract.cfm?uri=oe-19-s4-a991
https://doi.org/10.1016/j.mejo.2008.07.065



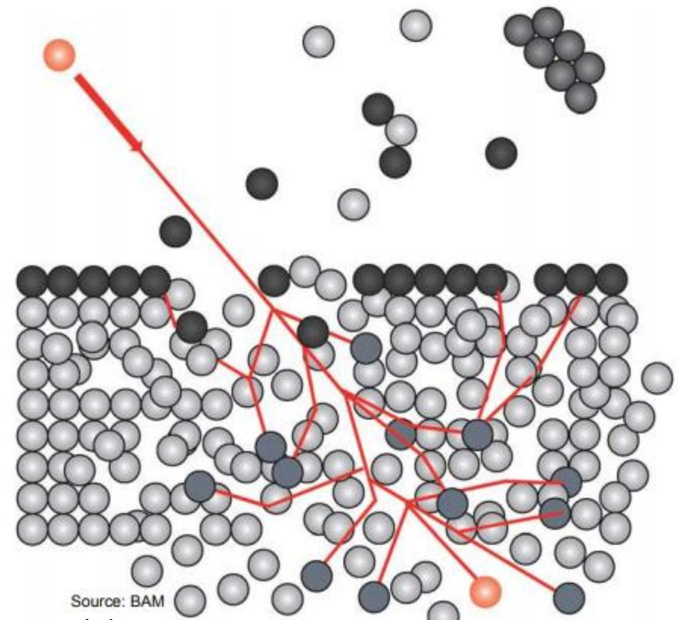
(Up) Solar cell application, Possible methods of circumventing the 31% efficiency limit for thermalized carriers in a single–band gap absorption threshold solar quantum conversion system, Lewis Science (2007) DOI: 10.1126/science.1137014

Lindsay : Intro to Nanoscience, Chapter 5 see more detail in Gabor Kiss: Micro and Nanotechnology

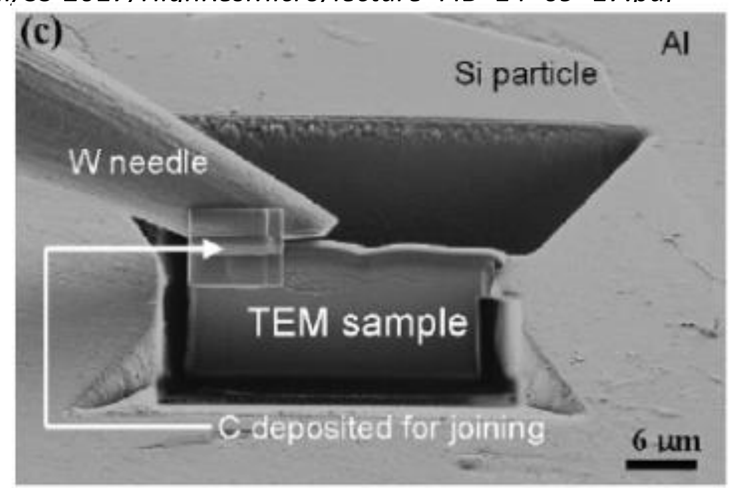
Focused Ion Beam (FIB)

Accelerate ions that locally remove material to form nanostructures. Focused sputtering.
Similar to an e-beam lithography system, but ions are accelerated instead of electrons. Typical ion energy: 5-30keV
Large mass difference between e and ion m_e-> $M_{ion} \approx 10000 \times m_e$
→ $\lambda_{ion} << \lambda_e$
→ Lorenz force has weaker effect, mostly electrostatic focusing
→ Less penetration than for e's.
→ Large momentum transfer: momentum transfer kicks atoms out (Like snooker.)
→ Localized ion milling with ~ few 10nm resolution limited by volume.
Mostly Ga^+ ions: easy to melt, Ga is middle of periodic table → momentum transfer is optimized for most elements.
Cons: Implantation of Ga ions.

Crossed beam systems SEM-FIB. Used:
- precise straight cutting of TEM samples.
- Electron beam assisted CVD e.g. C or Pt can be nanowritten on the surface.
- IC editing.

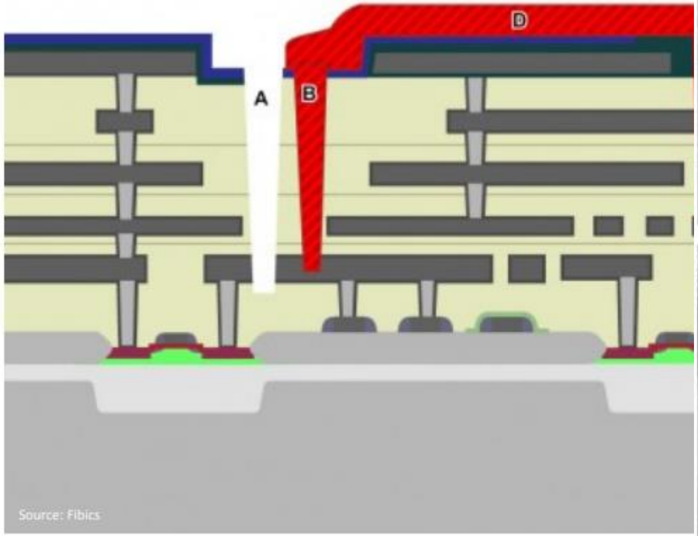


(Up) Ion-solid interaction.
Pros: Creation of secondary electrons (→ imaging); Removal of surface atoms, clusters; Creation of secondary ions (imaging)
Cons: ion implantation, Amorphisation, Scattering.
(Down) TEM sample fabrication by FIB
http://www.uni-stuttgart.de/mawi/aktuelles_lehrangebot/documents/LSII/SS-2017/HighResMicro/lecture_FIB_14_09_17.pdf

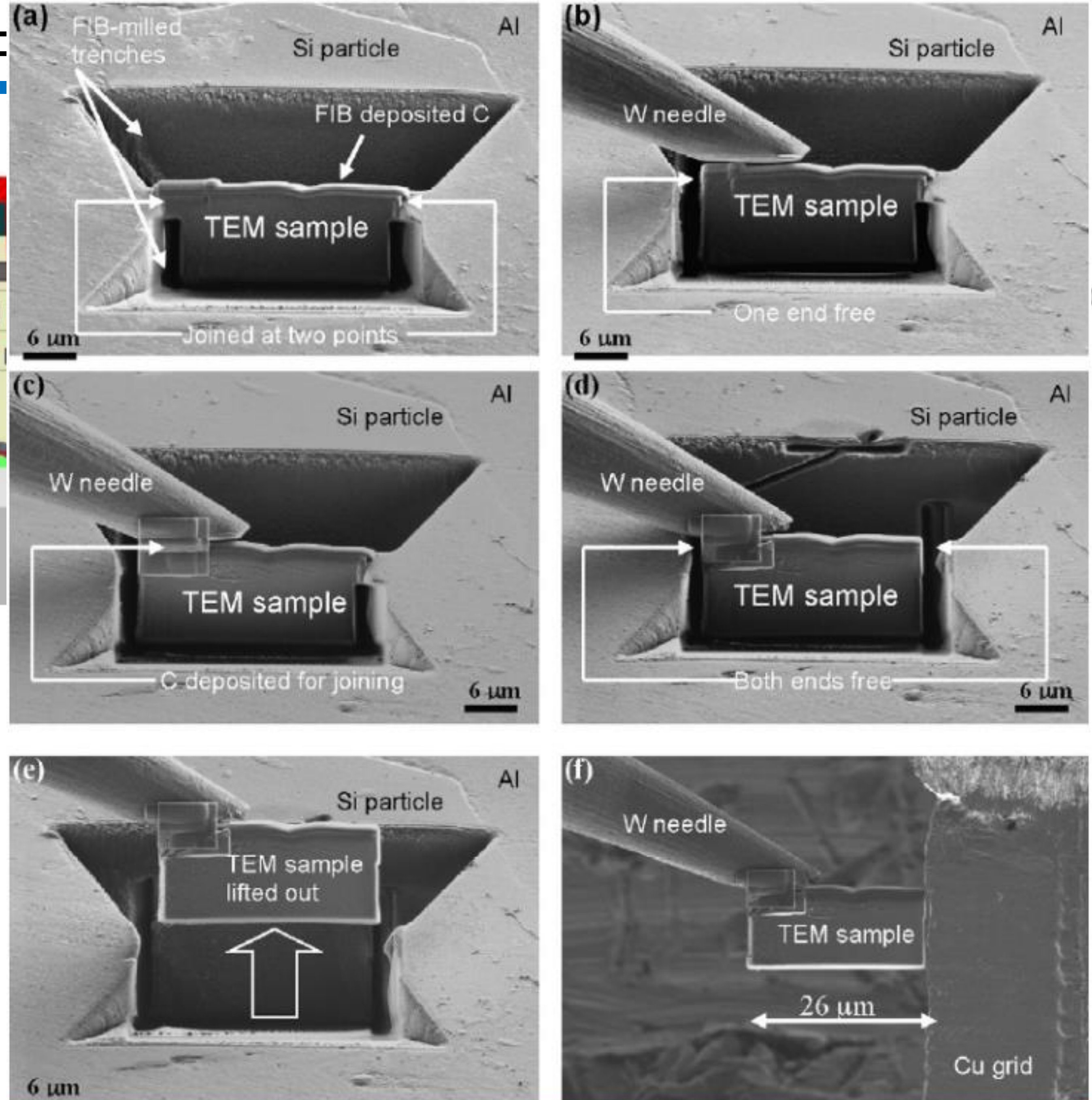


Lindsay : Intro to Nanoscience, Chapter 5 *Available at ELTE or MTA EK MFA*

Focused Ion Beam (F



FIB assisted IC editing



Sample preparation for TEM

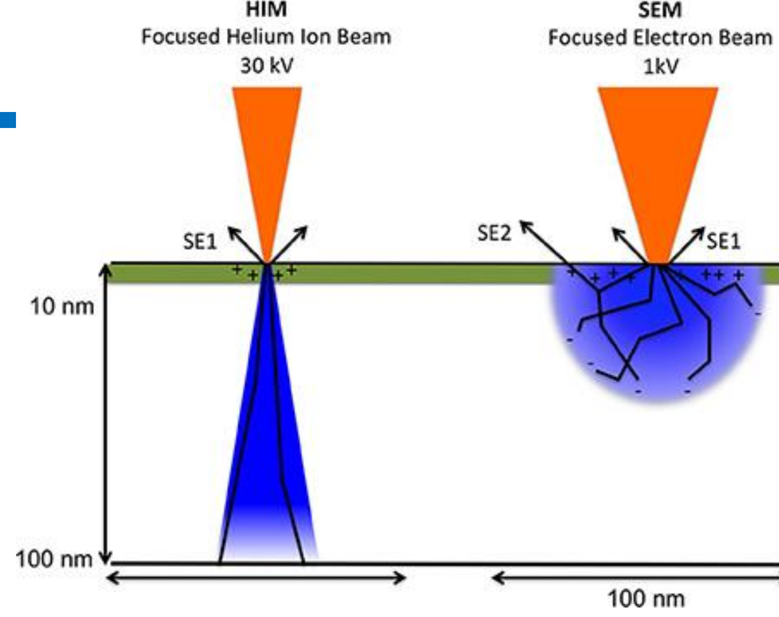
FIB - Helium ion microscopy (HIM)

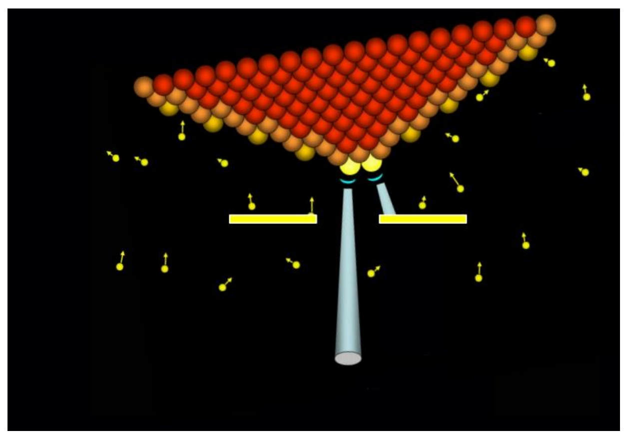
It uses advantages of FIB in imaging. Detect secondary electrons.
Observation possible at sub-nanometer scale
Advantages compare to SEM:

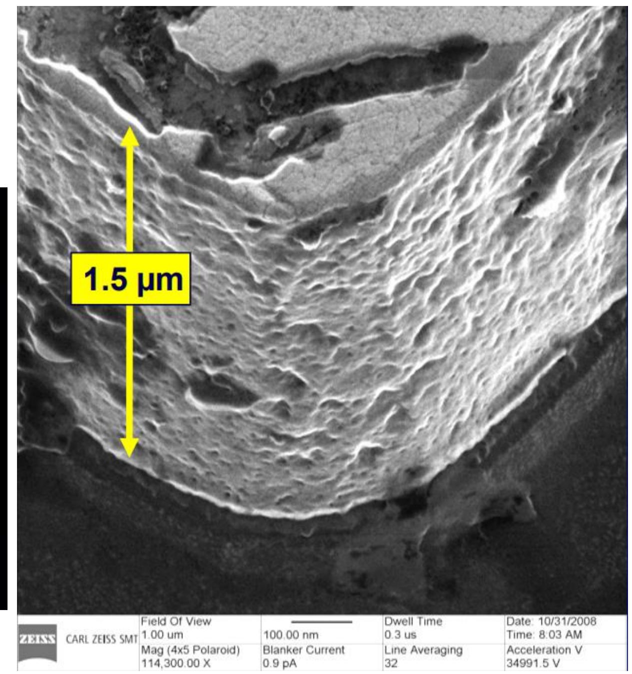
+ wave length limit smaller than for SEM (no adverse diffraction)
+ Smaller interaction volume than for SEM, secondary electrons only generated from the surface -> sharp images
+ Due to light weight of helium, negligible damage of the sample structure compared to FIB
+ Special, well-focused source: helium ions generated in a region of a single atom.

Performance:

→ Surface resolution 0.24nm (Zeiss 2009) much better than SEMs.
→ Depth of field is 5x better than for SEM (more collimated / small convergence angle)







(Up) Secondary electron generation comes from a much smaller volume for HIM as for SEM. Only surface layer.
https://www.researchgate.net/figure/Schematic-comparing-between-helium-ion-beam-and-electron-beam-and-charge-distribution_fig9_267743550
(Left) Atomic sized source: voltage-biased needle at cryo temperature in He gas → field ionization. (Right) Example of field of depth. Image size 1um, depth 2.5um.
DETAILS:
https://microscopy-analysis.com/editorials/editorial-listings/principles-and-applications-helium-ion-microscopy
https://www.nist.gov/sites/default/files/documents/pml/div683/conference/Postek_2009.pdf

Wikipedia

Lindsay : Intro to Nanoscience, Chapter 5

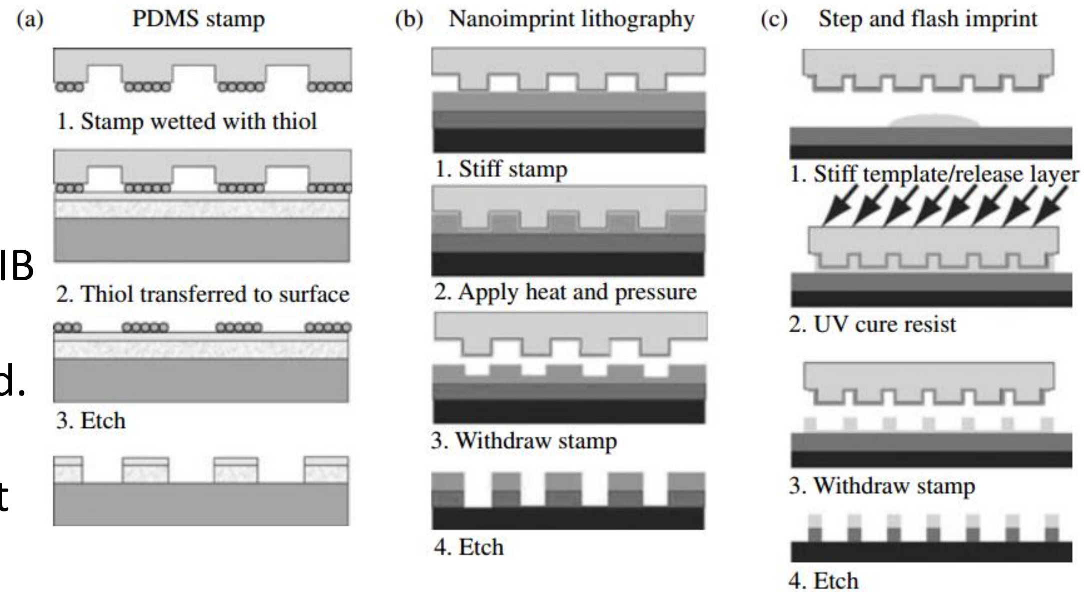
Nanoimprint lithography (NIL) -Stamping

Similar to original lithography invented by Gutenberg.
Example 1

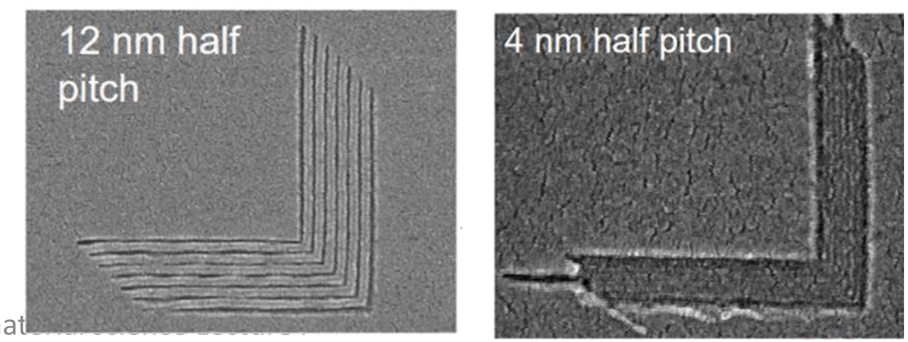
- Mold for the stamp is first cut directly into a hard substance like silicon using e-beam or FIB lithography
- PDMS is poured on the mold and cross-linked.
- Flexible rubber is resulted.
- Can be used as an office ink stamp to deposit chemicals in nanopatterns (see Panel (a) in Figure)
- With PDMS ~10nm resolution was achieved.

Advantages: No wavelength limit (High resolution), Parallel process, Cheap
Disadvantages: Not as reliable

It is used to produce various nanoscale structures e.g. for HD-DVD, photonic crystals, liquid crystal alignment in displays, patterning of nano resists, polimer reactors, microfluidics etc.



(Up) a) Imprint lithography to transfer chemicals. B) Example of nanoimprint lithography: a hard stamp is pressed to a soft resist, thinner region of the resist etched away and used as a mask. C) Similar to b) but liquid resist is used, which is crosslinked by light. Later on it is used as a mask.
(Down) HIM lithography defined mold imprinted in resist and 2nm Pt coated. Image is made by SEM which does not have the proper resolution to resolve.
http://sites.ieee.org/sfbanano/files/2016/07/NanoCON-Day-1-Wu.pdf



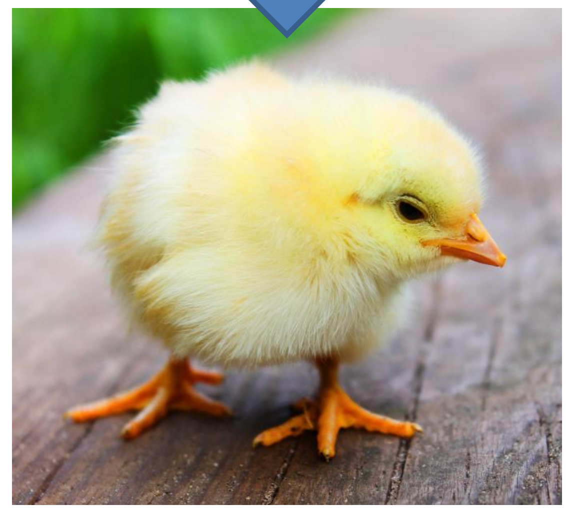
Wikipedia

Lindsay : Intro to Nanoscience, Chapter 5

Bottom-up approach

„making complex nanostructures starting from the random collisions of the components dissolved in a solvent. „
E.g. biology: from chaotic soup of an egg → macroscopic organism

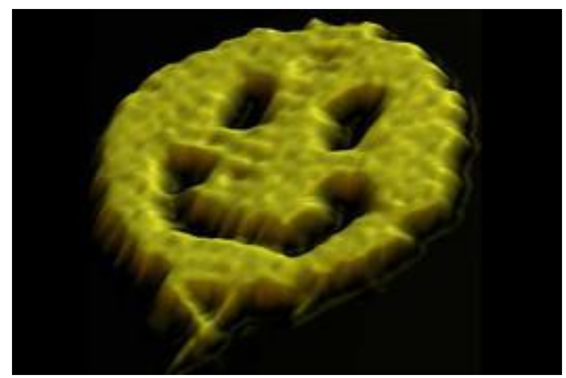
Goal/dream: Complex electronic circuitry that assembles itself from a chemical soup



Mechanism: Entropy-driven processes, special balance between:
- Entropy at a temperature
- Binding energies

in order to have
- reasonable stable structures at room temperature
- weak enough bonds to allow the system to explore large number of configuration to get to the desired configuration of lowest free energy (e.g. correct errors)

Carbon is a perfect starting ingredient, since it has large variety of ways to bond to other atoms (with 1, 2, 3, or 4 electrons). Therefore versatile structures can be built up.



Examples: DNA origami (see Introduction)

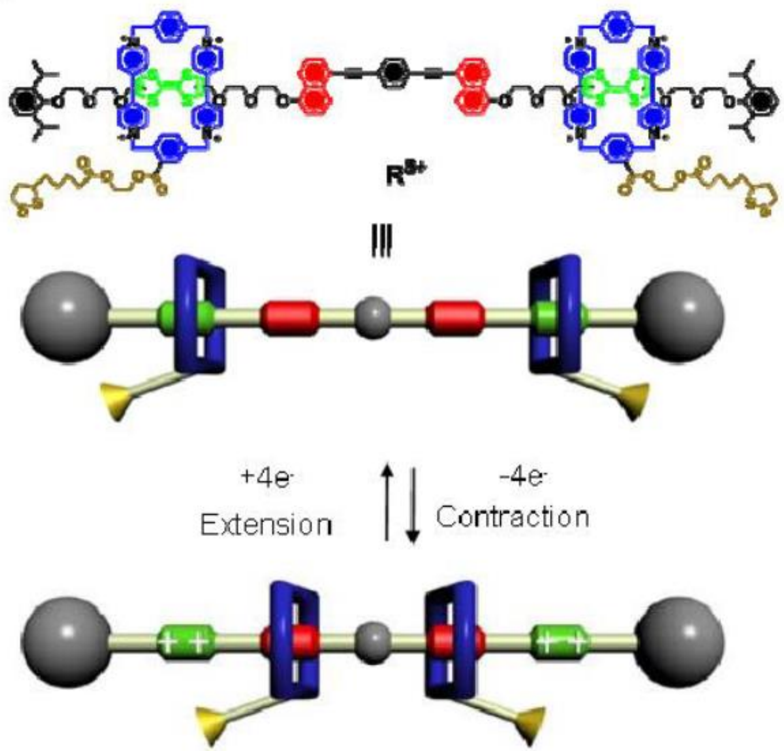
Wikipedia *Lindsay : Intro to Nanoscience, Chapter 6*

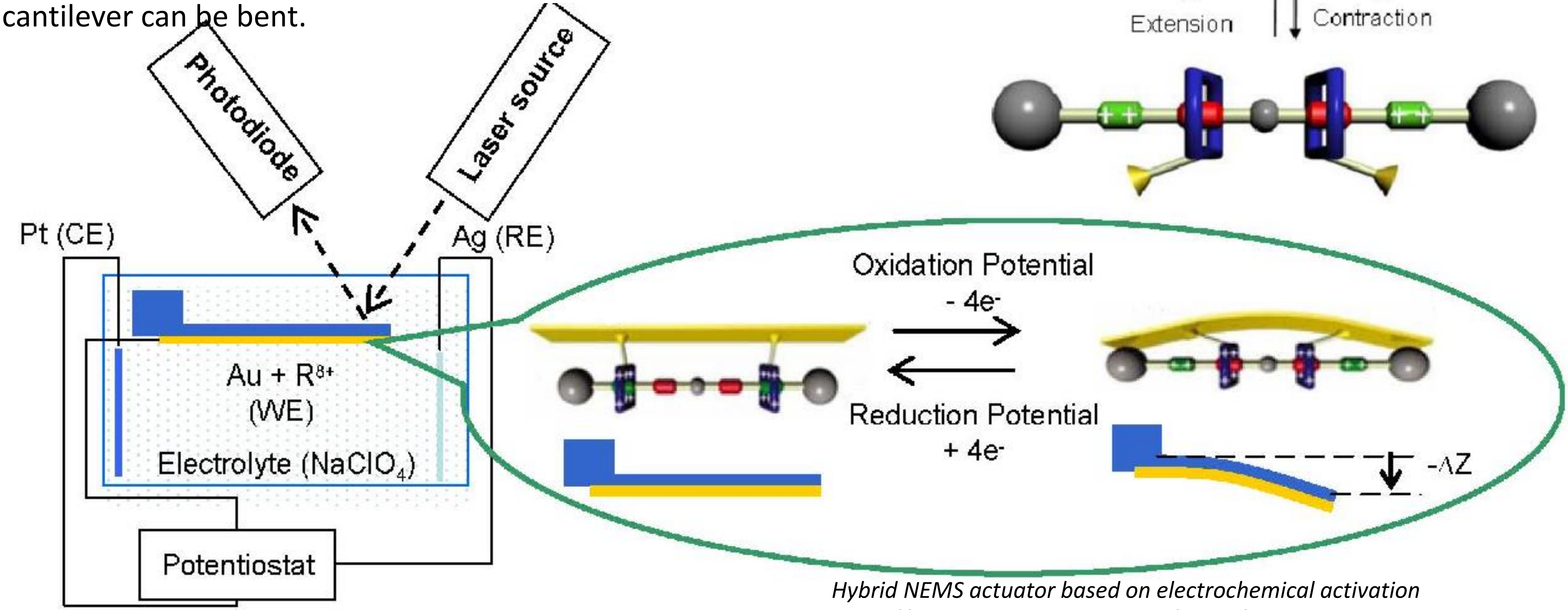
Power of organic synthesis

Example I: Nano-muscle based on rotaxane

It is based on a pair of rotaxane molecules (blue) free to slide on a shaft: switch from position green to position red as the oxidation state of the central molecule (TPR, gray middle) is changed from 8+ to 12+.

Using sulfur anchoring groups to gold surface, a NEMS cantilever can be bent.





Hybrid NEMS actuator based on electrochemical activation
https://www.semanticscholar.org/paper/Molecular-Muscle-based-(NEMS)-Juluri-Kumar/3cc658033253f35a740fc44148207bc6a7b71a43

Wikipedia

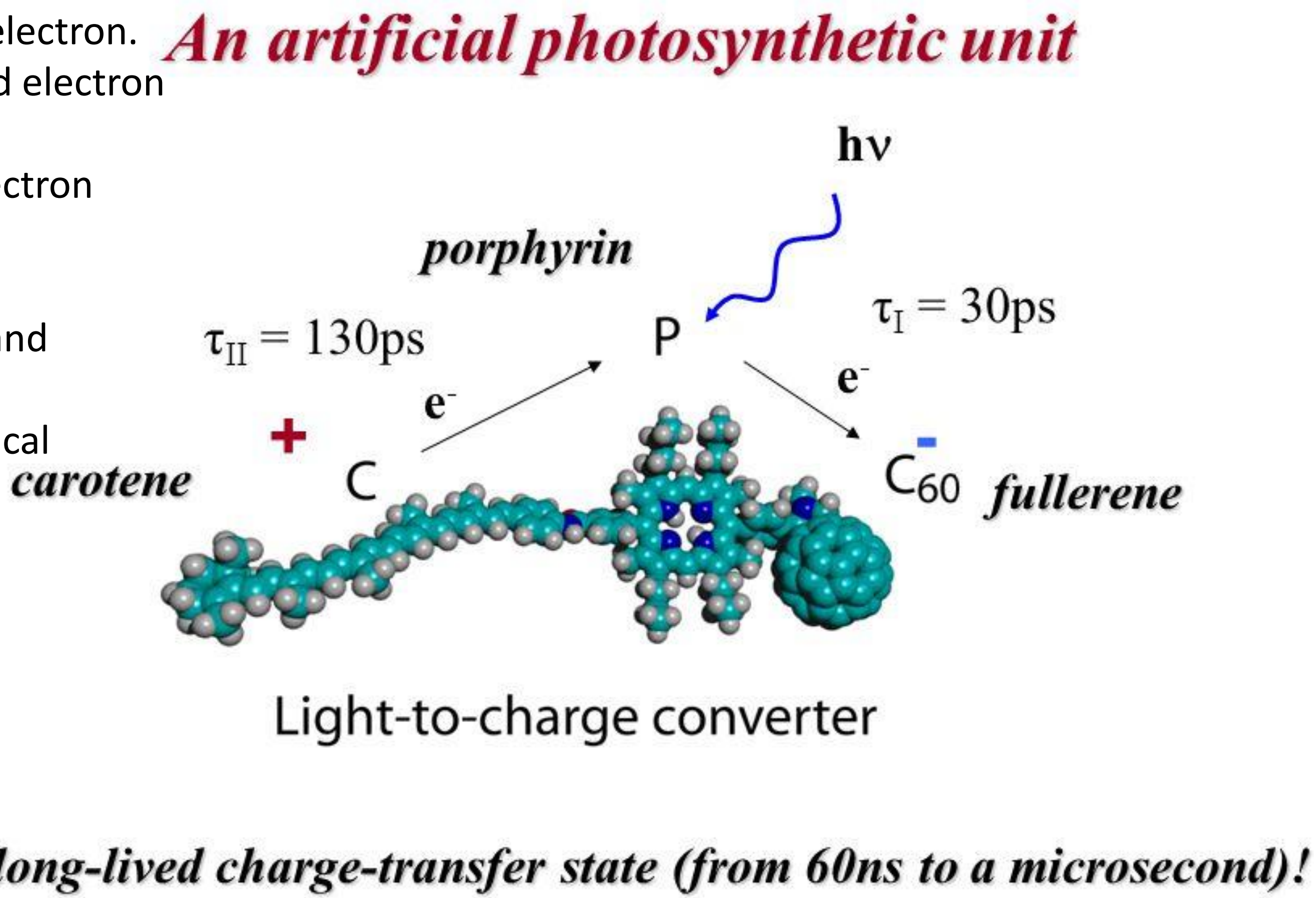
Lindsay : Intro to Nanoscience, Chapter 6

Power of organic synthesis

Example II: Light-to-charge converter

- Porphirin (P) absorbs light by exciting electron.
- A coupled fullerene grabs the excited electron before e in P decays to ground state
- A coupled carotene (C) injects an electron back to P
- P is now in its ground state, but:
- Carotene is now positively charged and fullerene is negatively charged.

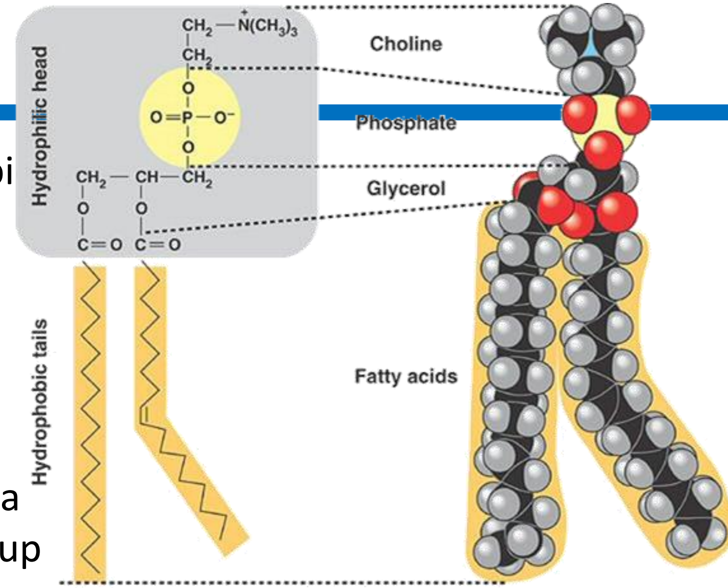
Charge separation can be used as chemical energy.



Basics of artificial photosynthesis with CPF carotene-porphyrin-fullerene structure
https://slideplayer.com/slide/5003798/

Wikipedia *Lindsay : Intro to Nanoscience, Chapter 6*

Amphiphiles in aqueous solutions

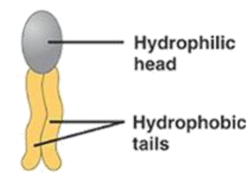


- Amphiphiles are molecules that contain both a hydrophilic and a hydrophobic component.

E.g. detergents: hydrophobic component binds oil/grease while the hydrophilic part helps to pull the complex into solution.

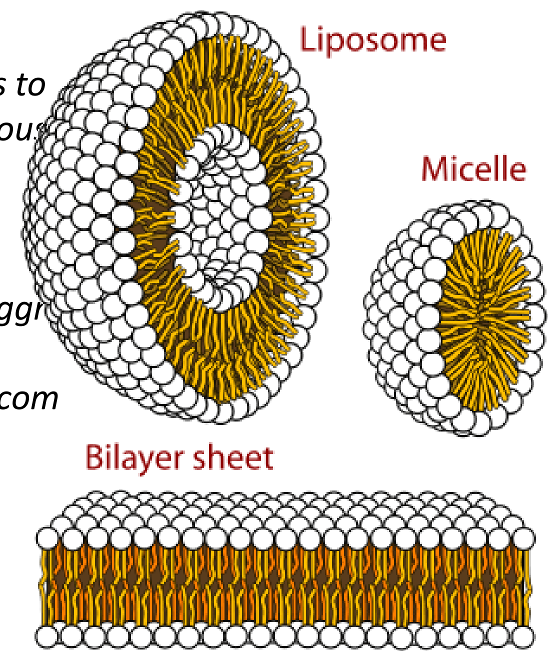
Walls of cells: self-assembled from amphiphilic molecules.
Building blocks are phospholipids, which consist of a pair of long alkane chains (repeated units of methylene, –CH2–) connected together by a head group that contains a number of charged atoms on the phosphate group

(Up) Structure of phospholipid molecule



Different structures depending on the geometry of building molecules:
Micelles are clusters that consist of a single layer of amphiphiles in which all the hydrophobic tails point inwards to exclude water completely while the hydrophobic heads point outwards
Liposome are bilayer spheres that enclose water
They self-assemble. With molecular dynamics the final form can be tested and simulated.

(Right) Amphiphiles spontaneously form small vesicles that are impervious to water when placed in aqueous solutions
https://www.phospholipid-research-center.com/phospholipid/aggregates/
http://eloifeitosa.blogspot.com/p/research.html



$$\frac{v}{a_0 \ell_c} < \frac{1}{3}$$ → spherical micelle

$$\frac{1}{3} < \frac{v}{a_0 \ell_c} < \frac{1}{2}$$ → non-spherical micelle

$$\frac{1}{2} < \frac{v}{a_0 \ell_c} < 1$$ → liposome/bilayers

where v volume of molecule, a_0 area of the head group, l_c is the length of hydrocarbon chain.

Lindsay : Intro to Nanoscience, Chapter 6

Mitochondrion

·A self-assembled nanochemistry machine

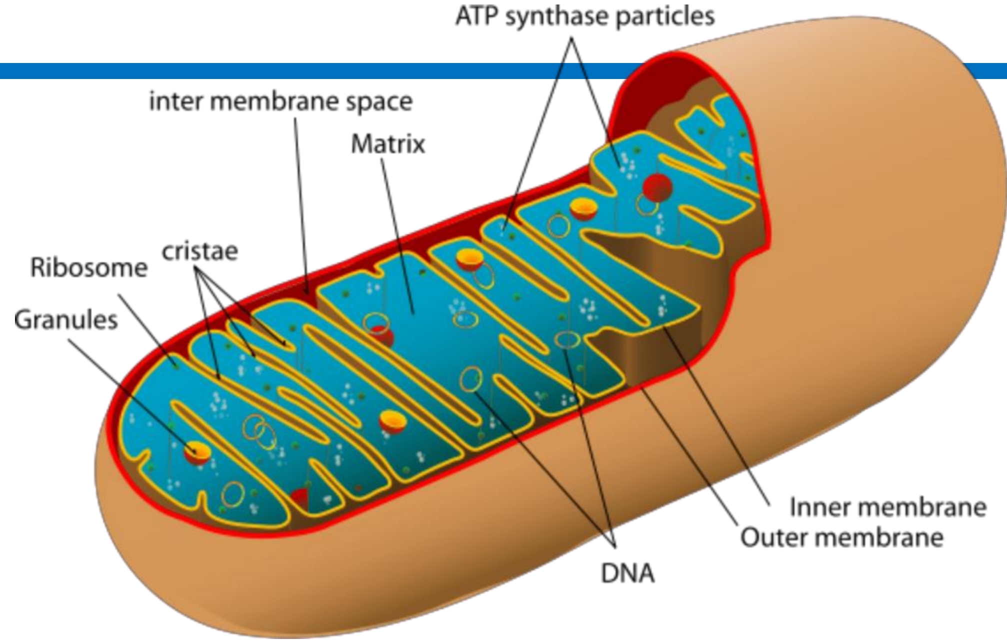
Inside eukaryotic cells (like ours), outside of the nucleus. (They carry their own DNA. "Presumably, they became incorporated into anaerobic organisms as a symbiotic partner that helped these cells survive the increase in atmospheric oxygen that occurred a few hundred million years ago.")

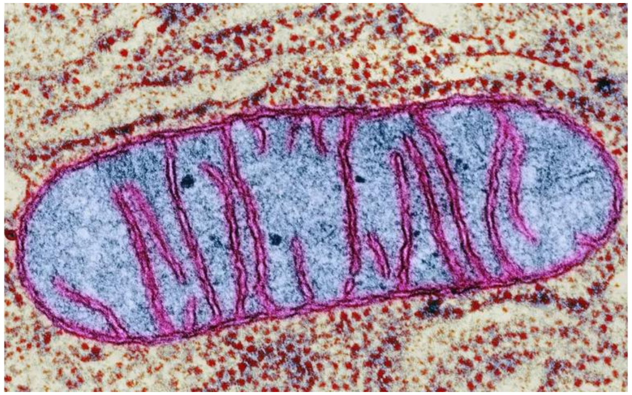
Machines that allow us to use atmospheric oxygen to complete the oxidation of sugars to produce biological energy.

Largely assembled from phospholipids: two sets of lipid bilayer membranes.

Outer one is a filter, only allowing small molecules into the intermembrane space.

Protons are pumped from the matrix into the intermediate space. The gradient of protons between intermembrane space and inner part drives synthesis of ATP molecules. ATP is transported out of mitochondrium and serve as source of energy.





(Up) Structure and TEM image of mitochondrion
https://www.thoughtco.com/mitochondria-defined-373367

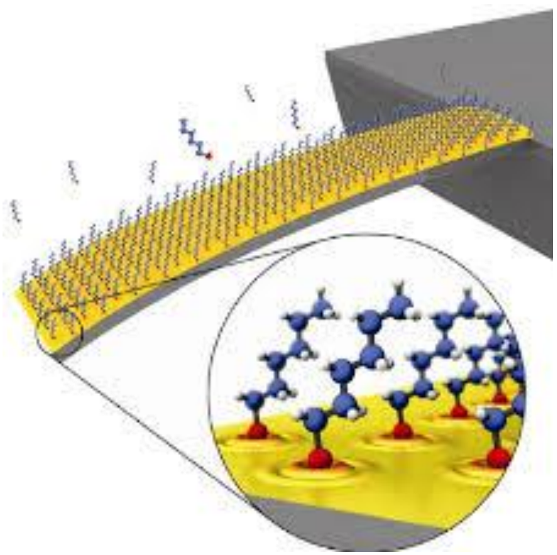
Wikipedia

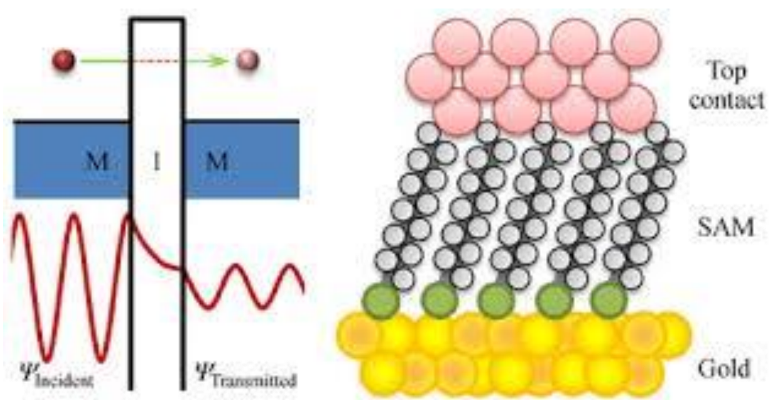
Lindsay : Intro to Nanoscience, Chapter 6

Molecular monolayers

Non-interacting molecules chemically attracted by a surface
E.g. alkane chains (-CH_2-) with thiol groups (-SH) on gold surface. From ethanol solution few hours a monolayer forms on the surface.
Good to modify chemical property of the surface.
Depending on the end group e.g. extremely hydrophobic / hydrophilic.
Such molecular monolayers also used in molecular electronics for ensemble measurement.

(Down left) Alkane chain on Au surface on cantilever as biochemical sensor based on surface stress. (Down right) A way to test molecular electron transport https://www.researchgate.net/figure/Artistic-view-of-an-alkanethiol-self-assembled-monolayer-SAM-on-a-gold-coated_fig1_230938526

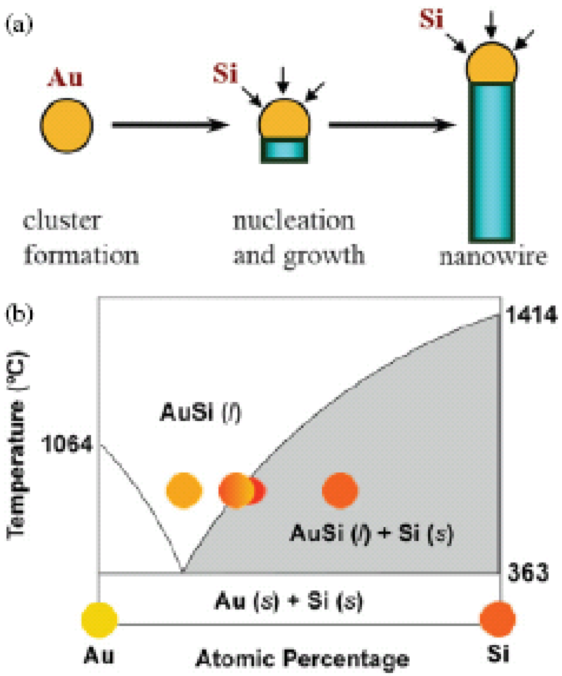




Wikipedia

Lindsay : Intro to Nanoscience, Chapter 6

Synthesis of Nanowires



J. Phys. D: Appl. Phys. 39, 387

Vapor-liquid-solid (VLS) growth:

- Catalyst metal nanoparticle
- Presence of vapor source of semiconductor
- eutectic mixture (metal + semicond. here): a homogeneous mixture with a melting point lower than those of the constituents.
- eutectic temperature: the lowest possible melting point over all of the mixing ratios
- Heated above the eutectic T
- Supersaturates -> nucleation of semiconductor
- Growth the NW with droplet on the top

Reactants: same precursors as in other processes,
CVD (Chemical vapour depos.), MBE, MOVPE, CBE

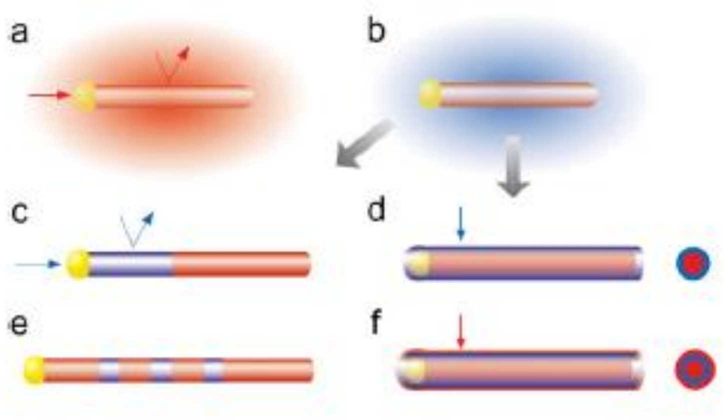
Competing interfaces:

- Liquid-solid (at metal particle): elongation of the NW, metal particle determinates the diameter
  eg.: possible 3nm diameter Si
  well-defined crystallographic orientation
- gas-solid (NW surface): thickening in the radial direction

Which dominates? p, flow, T, reactant

Lindsay : Intro to Nanoscience, Chapter 6

Synthesis of Nanowires



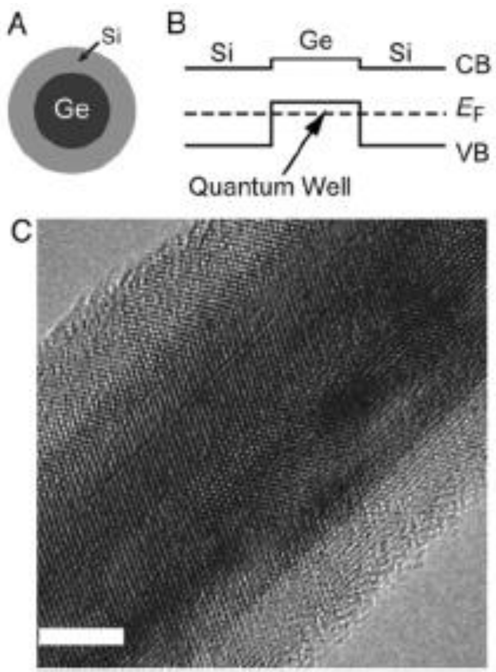
Crystalline heteroepitaxy can be achieved

Depending on preferred reaction interface (axial or radial growth):

- **Radial heterostructures**, core/shell (b→d)

eg.: Si/Ge core/shell structure -> hole gas

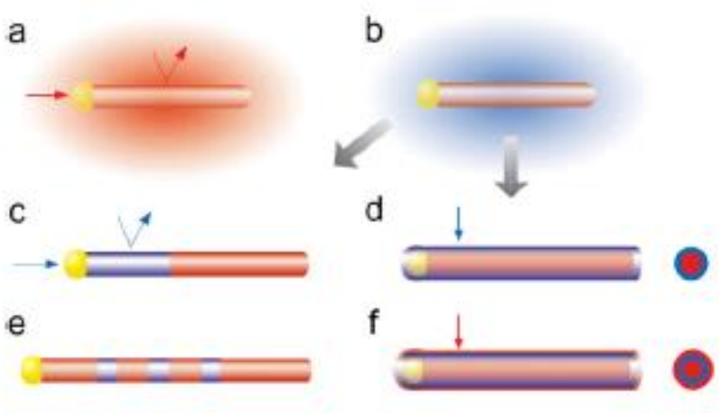
GaN ->light emitting diodes, SiO/Si

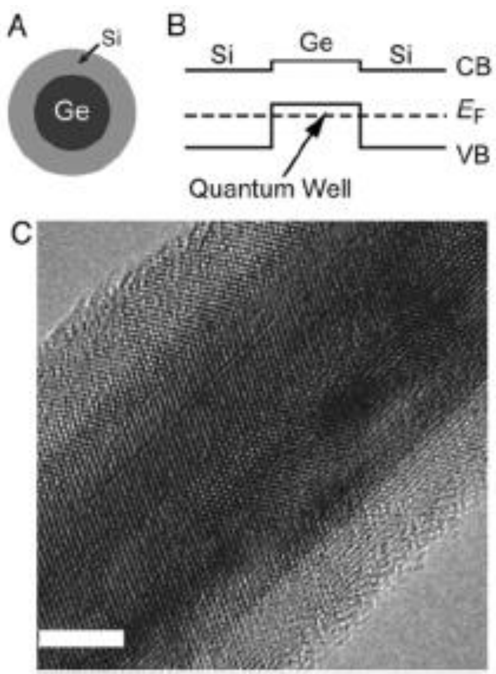


J. Phys. D: Appl. Phys. 39, 387

Lindsay : Intro to Nanoscience, Chapter 6

Synthesis of Nanowires





Nano Lett 2, 87 (2001)

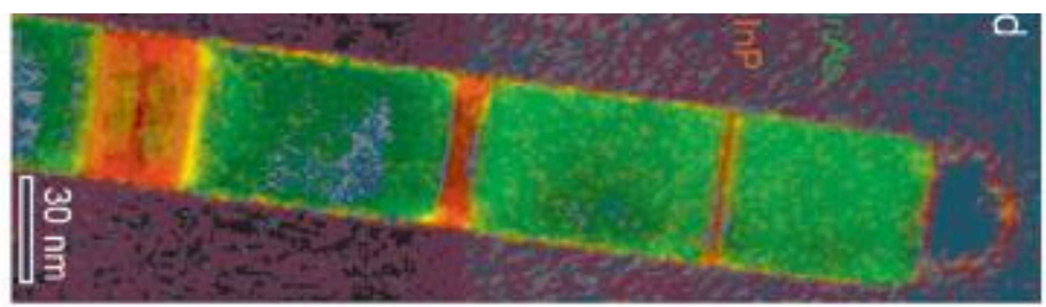
Crystalline heteroepitaxy can be achieved
Depending on preferred reaction interface (axial or radial growth):

- **Radial heterostructures**, core/shell (b→d)

eg.: Si/Ge core/shell structure -> hole gas
GaN ->light emitting diodes, SiO/Si

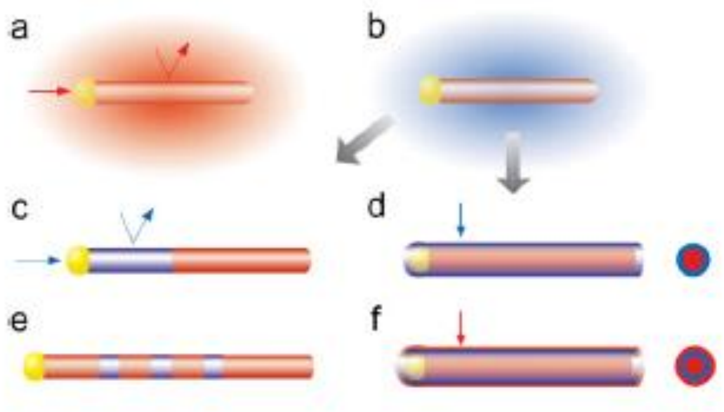
- **Axial heterostructures** (b→c)

with Au nanoparticle, wide range III-V, IV
eg.: InP/InAs interface of few atomic layers
0.6eV conduction band offset



Lindsay : Intro to Nanoscience, Chapter 6

Synthesis of Nanowires



Crystalline heteroepitaxy can be achieved

Depending on preferred reaction interface (axial or radial growth):

- **Radial heterostructures**, core/shell (b→d)

eg.: Si/Ge core/shell structure -> hole gas

GaN ->light emitting diodes, SiO/Si

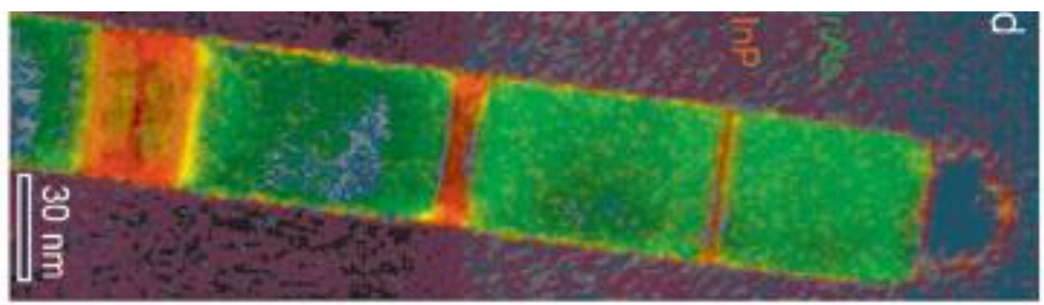
- **Axial heterostructures** (b→c)

with Au nanoparticle, wide range III-V, IV

eg.: InP/InAs interface of few atomic layers

0.6eV conduction band offset

- High level of control on dimension, chemical composition
- Band structure engineering
- Combine heavily mismatched materials up to >11% mismatch
- Monolithic integration of III-V into Si
- Epitaxial growth with defined crystal symmetries

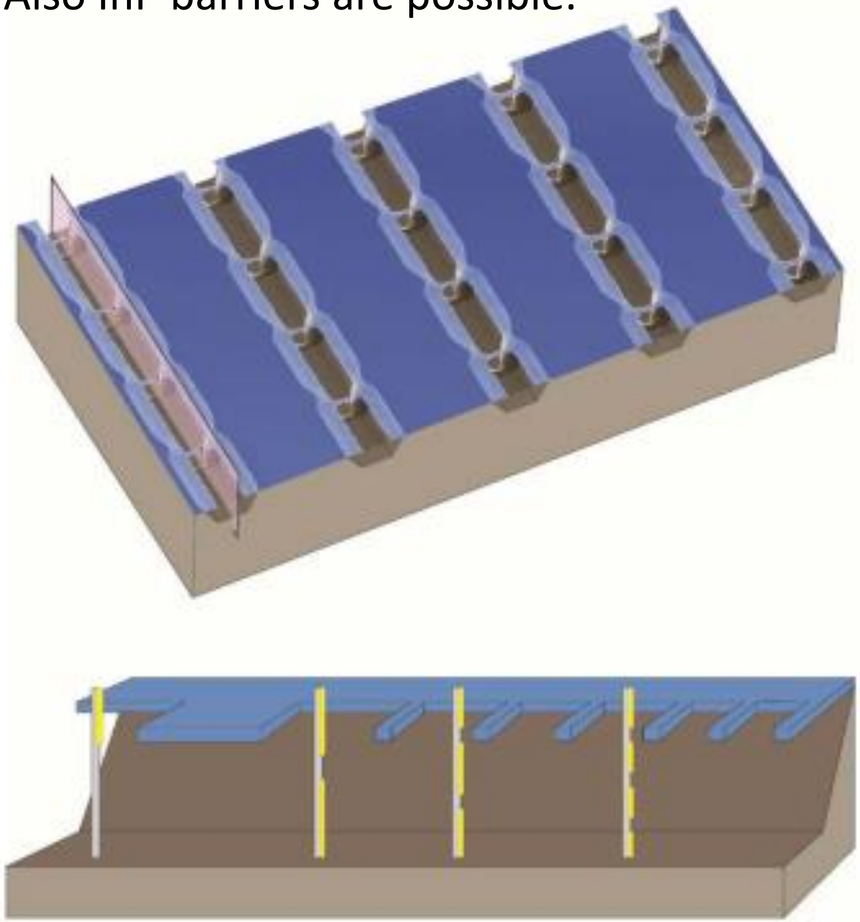


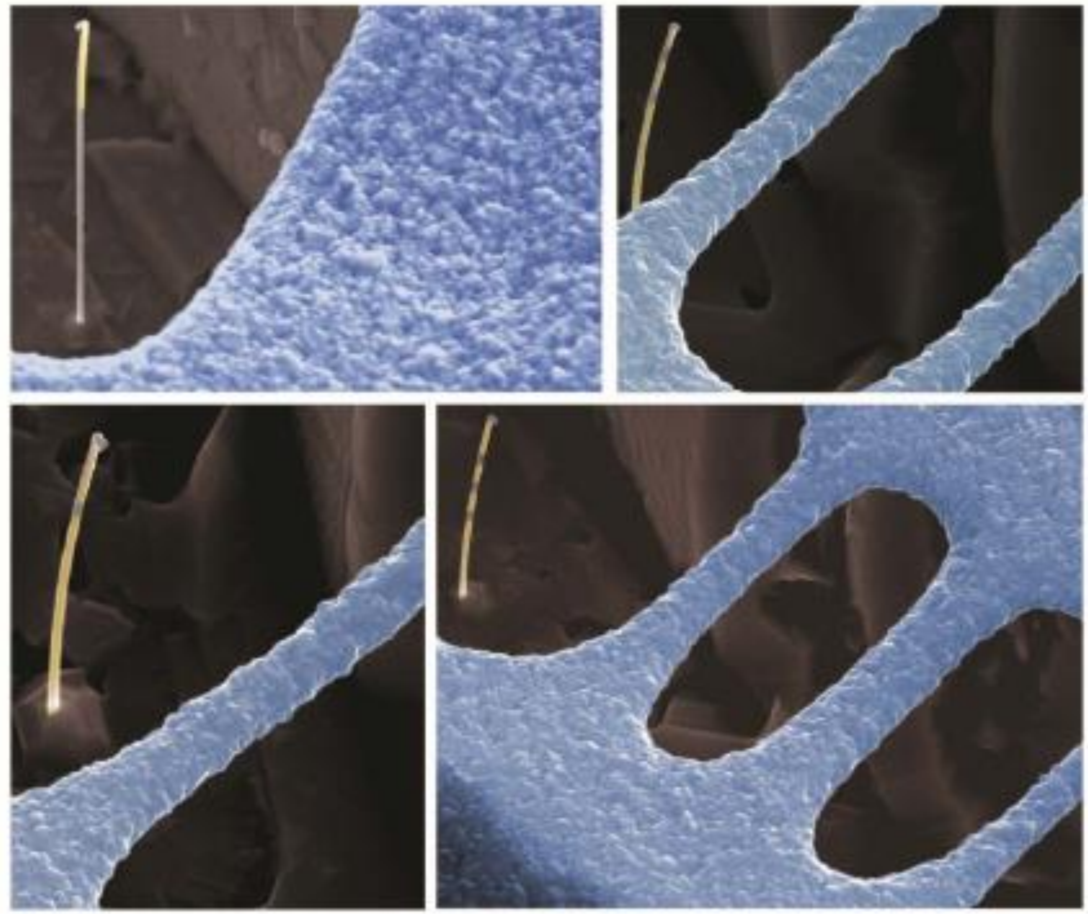
Nano Lett 2, 87 (2001)

Lindsay : Intro to Nanoscience, Chapter 6

Synthesis of Nanowires

InAs nanowires with epitaxial Al shell in certain sections
(define shadow mask - blue - on chip before growing NW; then evaporate Al at an angle).
Also InP barriers are possible.





Unpublished from J. Nygard

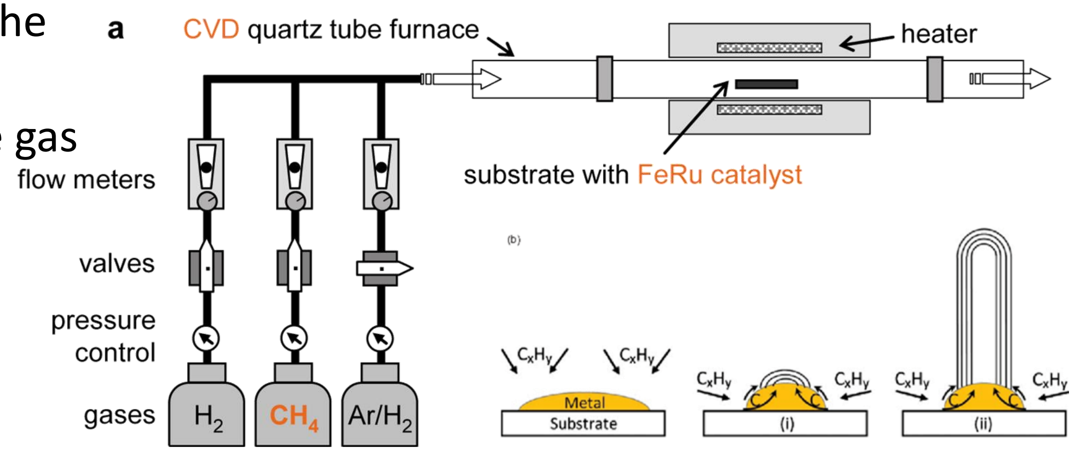
Lindsay : Intro to Nanoscience, Chapter 6

Chemical Vapour Deposition (CVD)

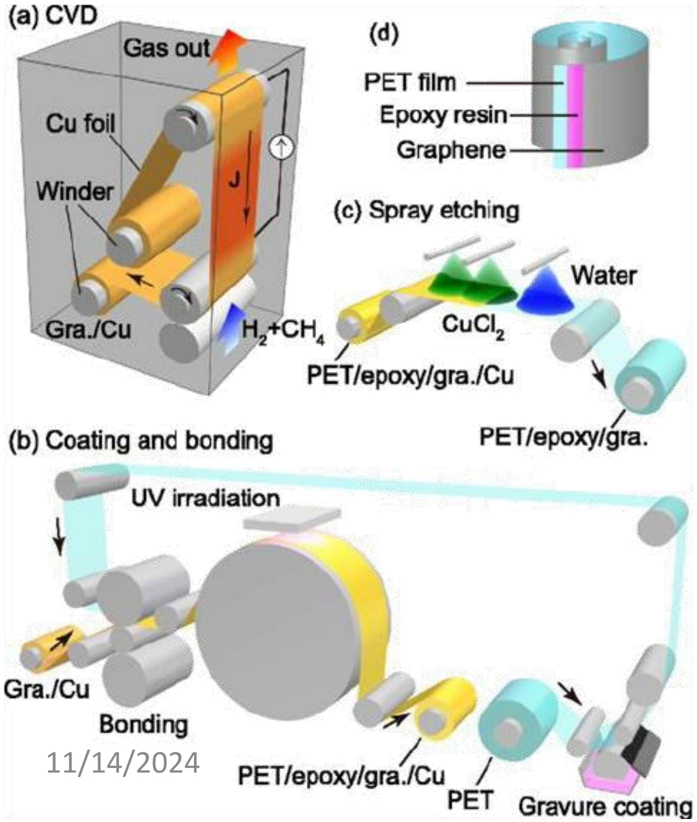
Creation of reactive chemical species close to the surface to be coated
E.g. growth of polycrystaline silicon from silene gas (600C and 1mbar)

$$SiH_4 \rightarrow Si + 2H_2$$

E.g.2: Growth of carbon nanostructures: graphene, nanotube



(Up) Typical CVD system to grow carbon nanostructures. Calayst particles with e.g. CH4 gas creates carbon nanotubes. The schematic growth process is shown bellow.
https://www.nano.physik.uni-muenchen.de/nanophysics/research/rep11.html
https://www.semanticscholar.org/paper/Chemical-vapor-deposition-of-carbon-nanotubes%3A-a-on-Kumar-Ando/8cad65216fe922b14c5c947330cc791341f621fb



(Down) Basic process of CVD growth of graphene on Cu substrate from CH4.
(Left) Continous roll-to-roll CVD growth and transfer of large area graphene
https://www.sciencedirect.com/science/article/abs/pii/S0379677915300138
https://www.researchgate.net/figure/Schematic-of-continous-roll-to-roll-CVD-growth-and-transfer-of-large-area-graphene_fig5_249286739