From Atoms to microfilms:
a journey in thin film deposition technology

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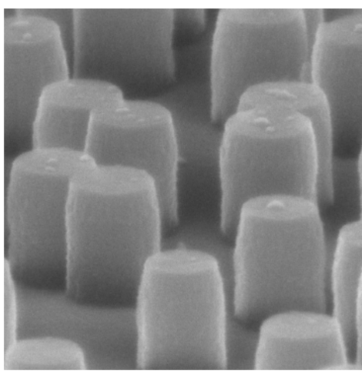
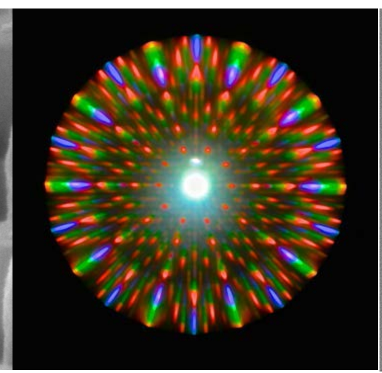
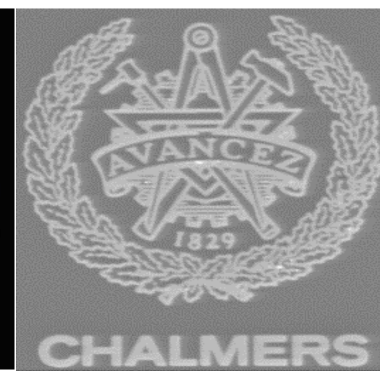
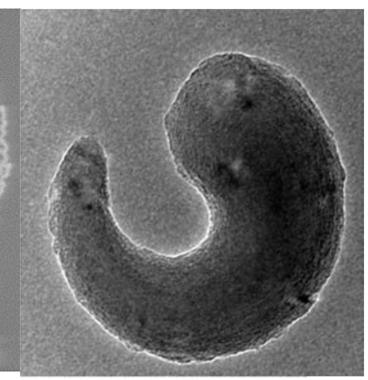
Bionanophotonic division, Physics Department
Chalmers University of Technology

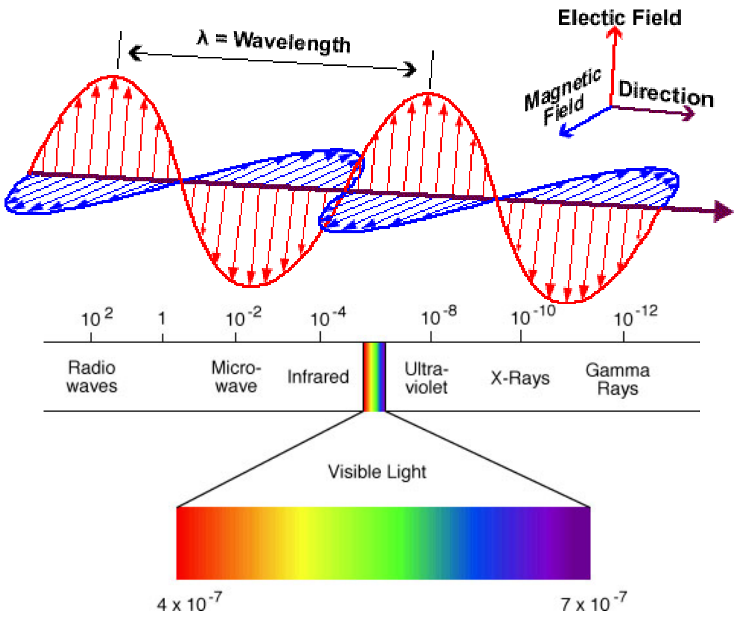
NNUM, Copenhagen, 7th May 2019

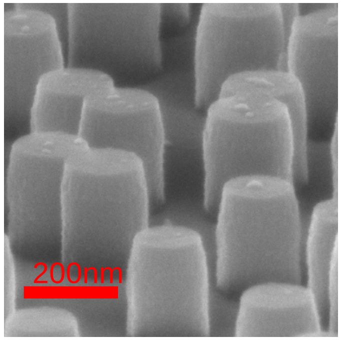


MICRONOVA
Centre for Micro and Nanotechnology
myfab
NORWEGIAN MICRO- AND NANOFABRICATION FACILITY
NorFab
DTU Nanolab
NNN
Nordic Nanolab Network

Optical antennas

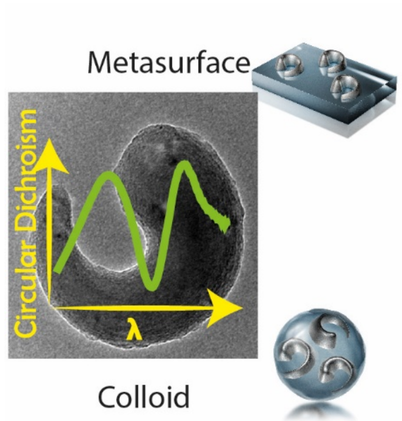


Si, GaAs, Ge, etc…



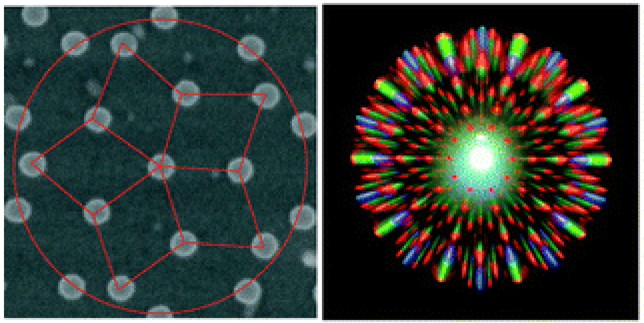
Light focused in a sub-wavelength volume (few nm)

Large-scale fabrication methods



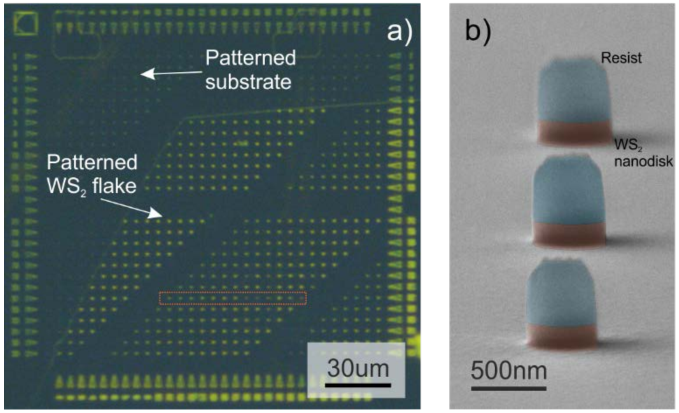
Verre *et al.,* Advanced Materials, 2017

Complex e-beam patterned assemblies



Verre *et al.,* ACS nano, 2014

Study of new materials as optical antennas



Verre *et al.,* Nature Nanotech., 2019

Complex interactions between optical antennas

Verre *et al.,* Nano Letter, 2015

Nordic Nanolab Network

A journery in thin film deposition

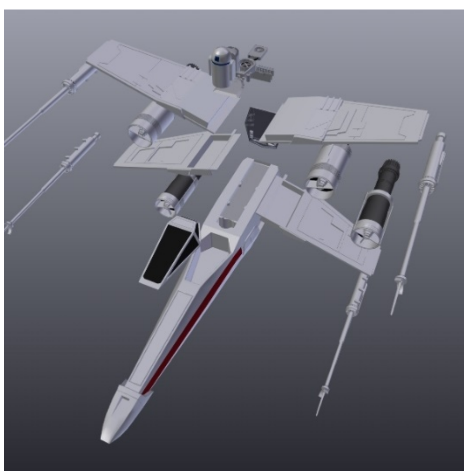
- Critical parameters
- Practical applications
- Research frontiers

These aspects discussed with a nanooptic prospective

Capitan: (user)

Monitors: pressure + thickness

Stage/sample control



Engine:ebeam or thermal evaporators

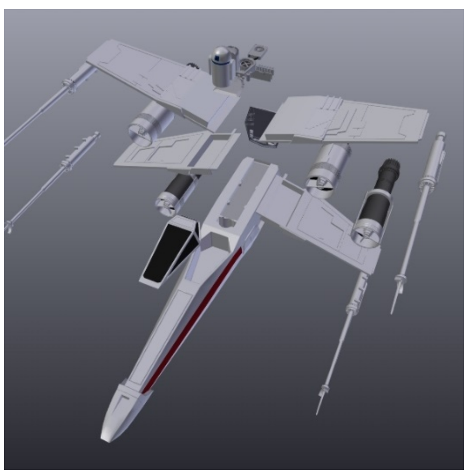
Fuel: materials sources

Think about the enviroment!!!

Monitors: pressure + thickness

Capitan: (user)

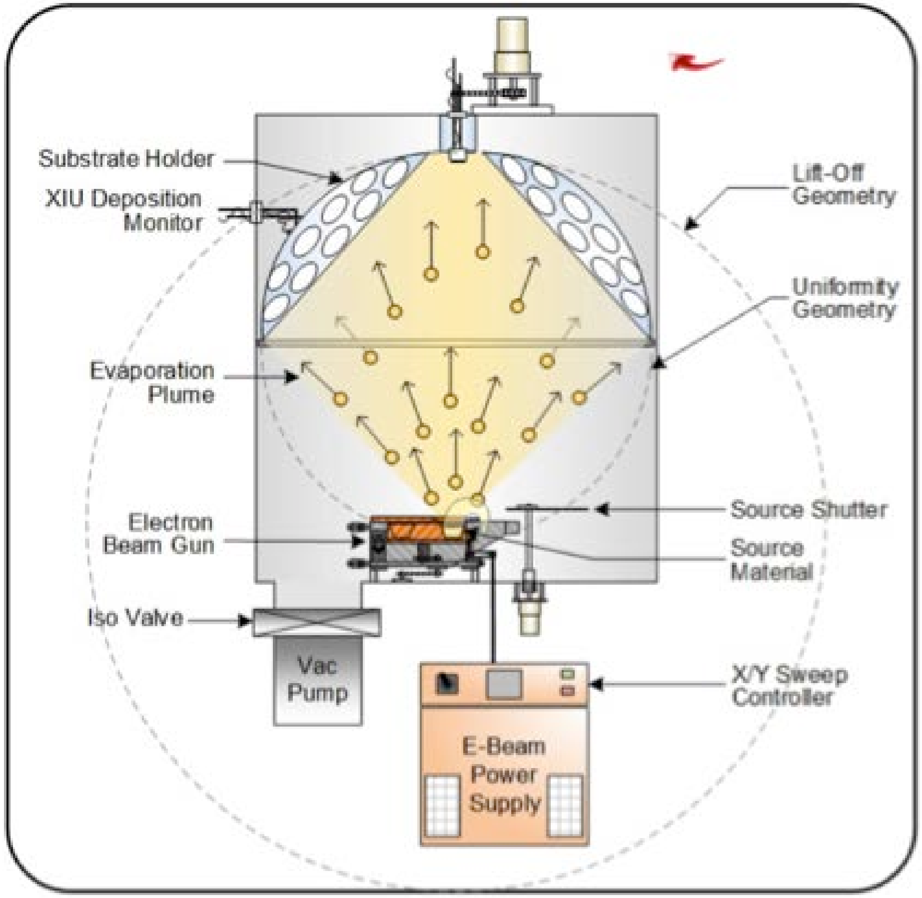
Stage/sample control



Engine:ebeam or thermal evaporators

Fuel: materials sources

Evaporation chamber



Semicore site

Wall chamers
Material & Geometry (high conductance)

Pumps:
ion pump, Ti sublimation, Cryopump, Turbopump, Rotary

Valves (mechanisms and inges)

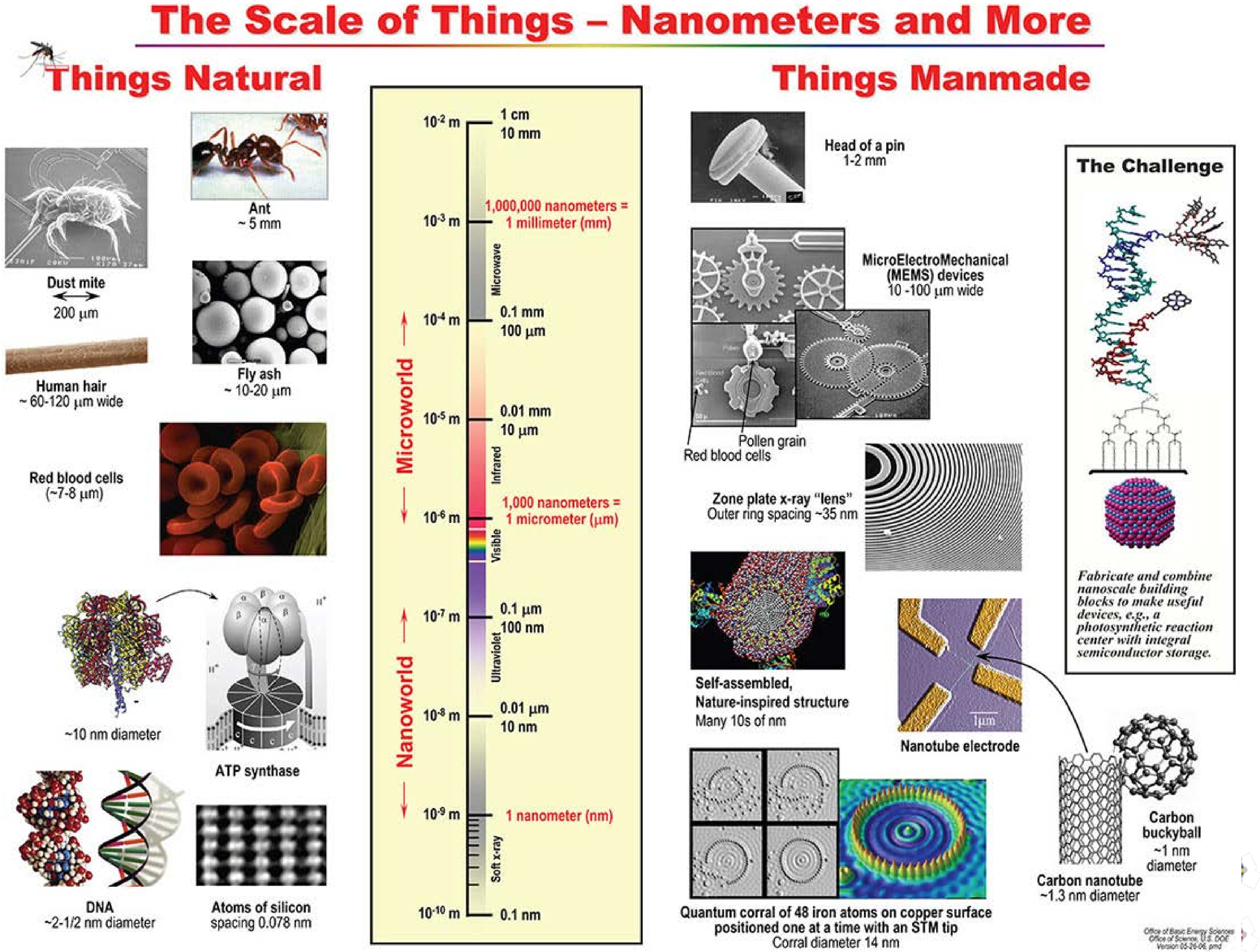
Pressure monitor: Pirani and hot-filament gauge

Ebeam evaporator: power supply and electron gun

Physical vapor deposition (PVD): thermal evaporation

Kinetic Data for Air as a Function of Pressure

Pressure (Torr)	Mean Free Path (cm)	Number Impingement Rate ($s^{-1} \cdot cm^{-2}$)	Monolayer Impingement Rate (s^{-1})
10^{1}	0.5	3.8×10^{18}	4400
10^{-4}	51	3.8×10^{16}	44
10^{-5}	510	3.8×10^{15}	4.4
10^{-7}	5.1×10^{4}	3.8×10^{13}	4.4×10^{-2}
10^{-9}	5.1×10^{4}	3.8×10^{11}	4.4×10^{-4}



The Scale of Things – Nanometers and More
Things Natural
Things Manmade
Ant
~ 5 mm
Dust mite
200 µm
Human hair
~ 60-120 µm wide
Fly ash
~ 10-20 µm
Red blood cells
(~7-8 µm)
~10 nm diameter
ATP synthase
DNA
~2-1/2 nm diameter
Atoms of silicon
spacing 0.078 nm
10-2 m
1 cm
10 mm
10-3 m
1,000,000 nanometers =
1 millimeter (mm)
Microwave
10-4 m
0.1 mm
100 µm
10-5 m
0.01 mm
10 µm
Infrared
10-6 m
1,000 nanometers =
1 micrometer (µm)
Visible
10-7 m
0.1 µm
100 nm
Ultraviolet
10-8 m
0.01 µm
10 nm
10-9 m
1 nanometer (nm)
Soft x-ray
10-10 m
0.1 nm
Microworld
Nanoworld
Head of a pin
1-2 mm
MicroElectroMechanical
(MEMS) devices
10 -100 µm wide
Pollen grain
Red blood cells
Zone plate x-ray "lens"
Outer ring spacing ~35 nm
Self-assembled,
Nature-inspired structure
Many 10s of nm
Nanotube electrode
1µm
Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm
Carbon nanotube
~1.3 nm diameter
Carbon
buckyball
~1 nm
diameter
The Challenge
Fabricate and combine
nanoscale building
blocks to make useful
devices, e.g., a
photosynthetic reaction
center with integral
semiconductor storage.
Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 05-26-06, pmd

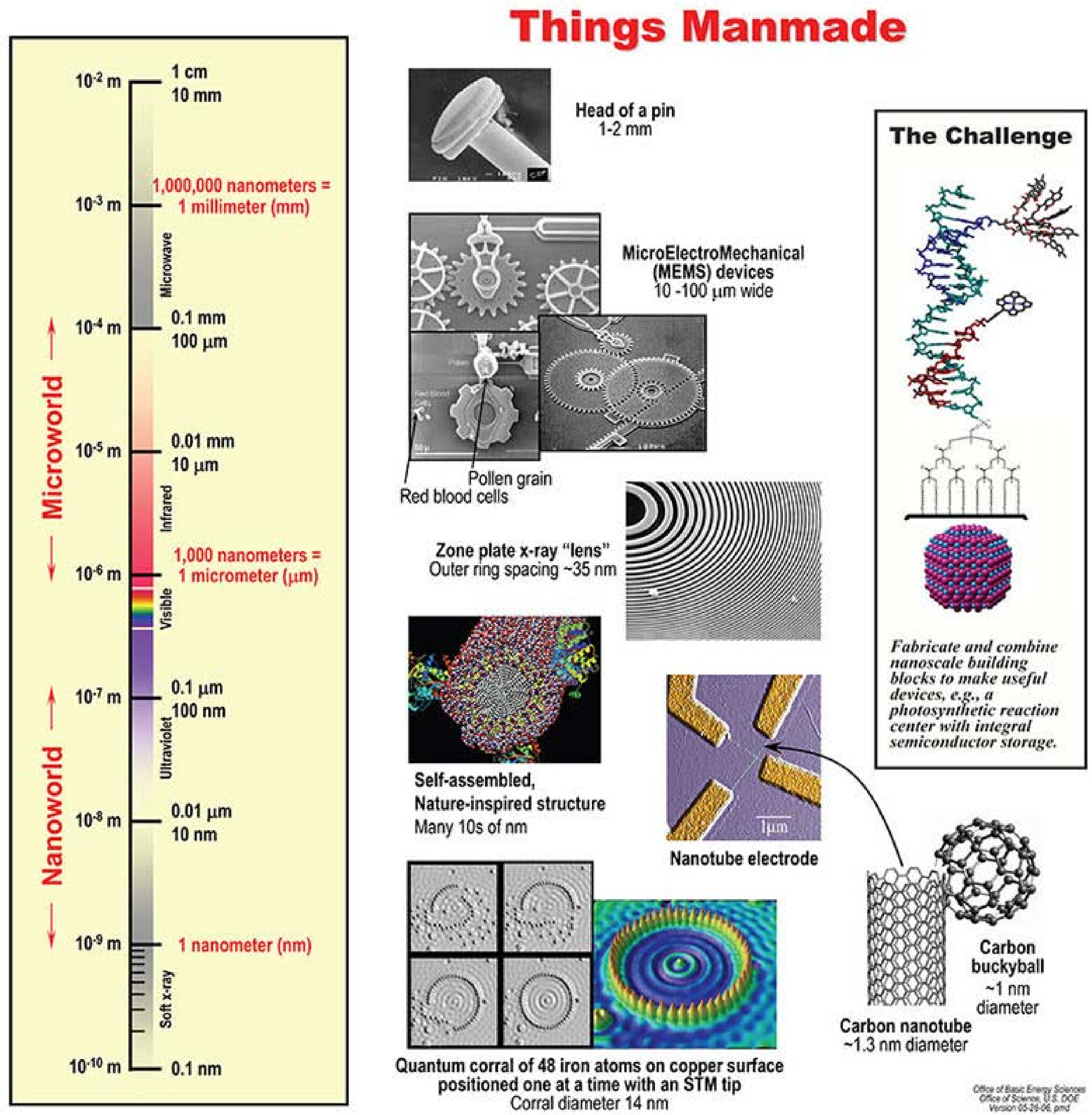
The Scale of Things – Nanometers and More

Microstructured films

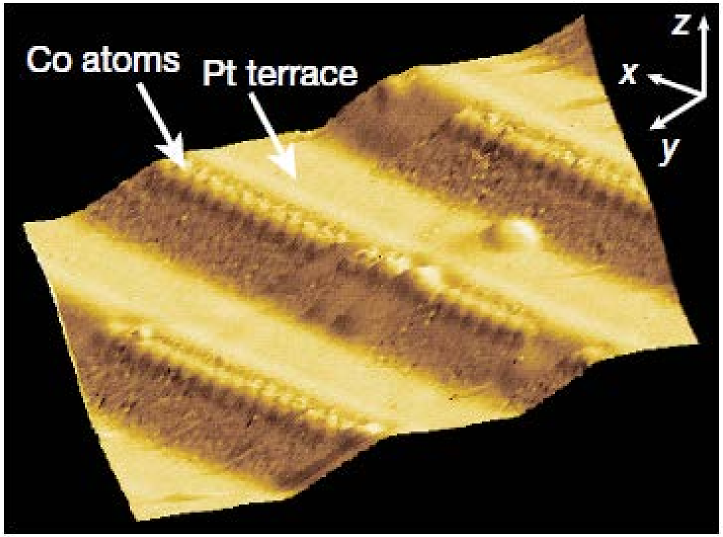
Multilayers

Thin film

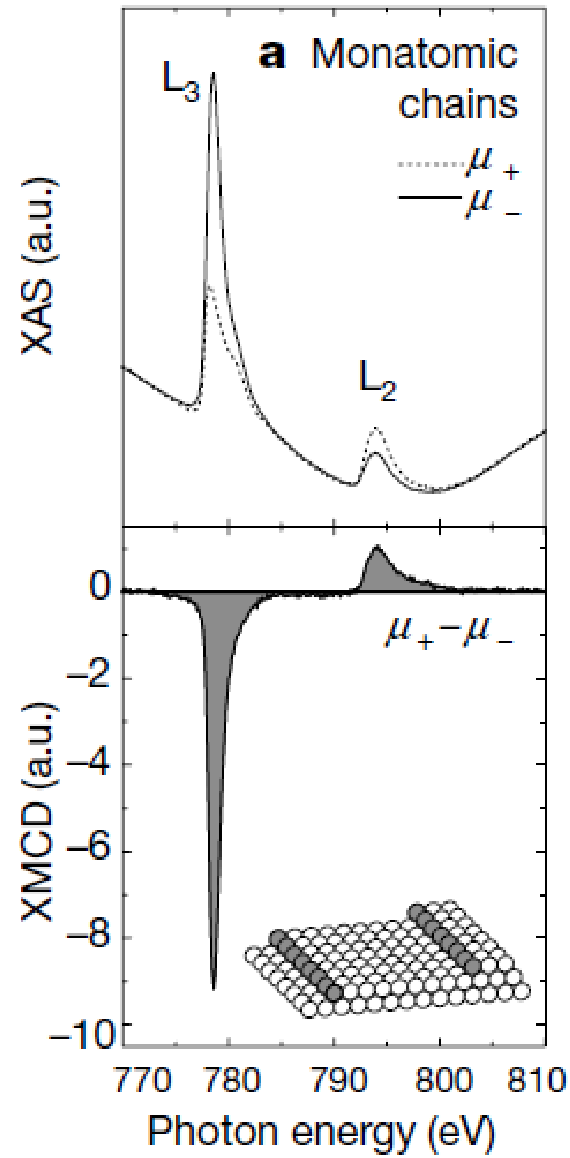
Sub-monolayer



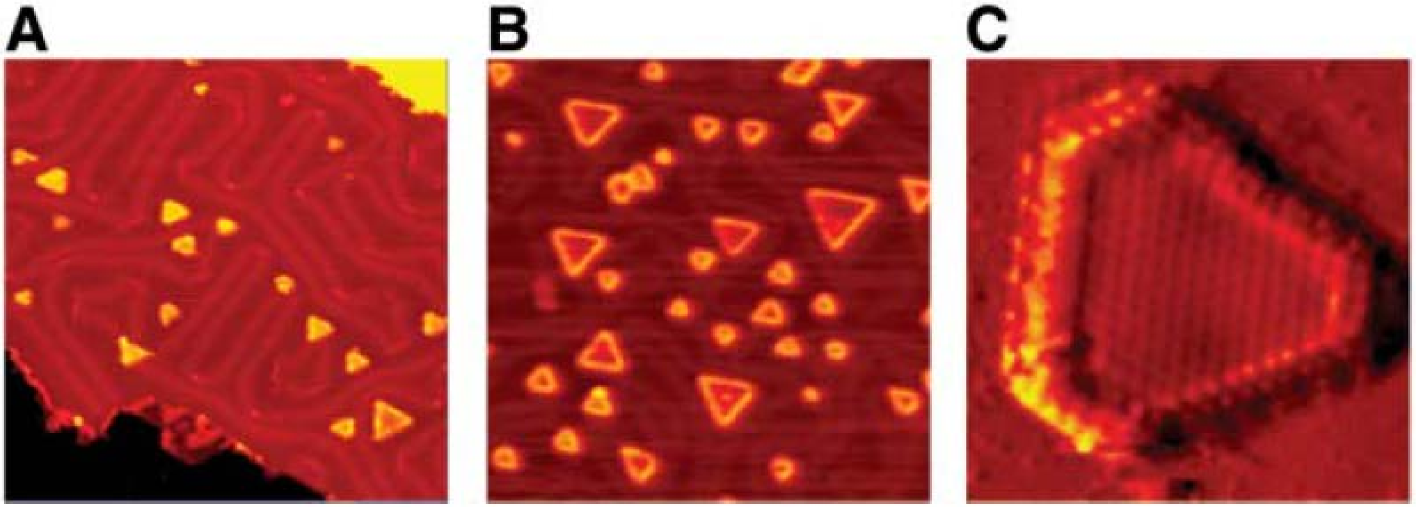
Submonolayer: magnetic superlattices



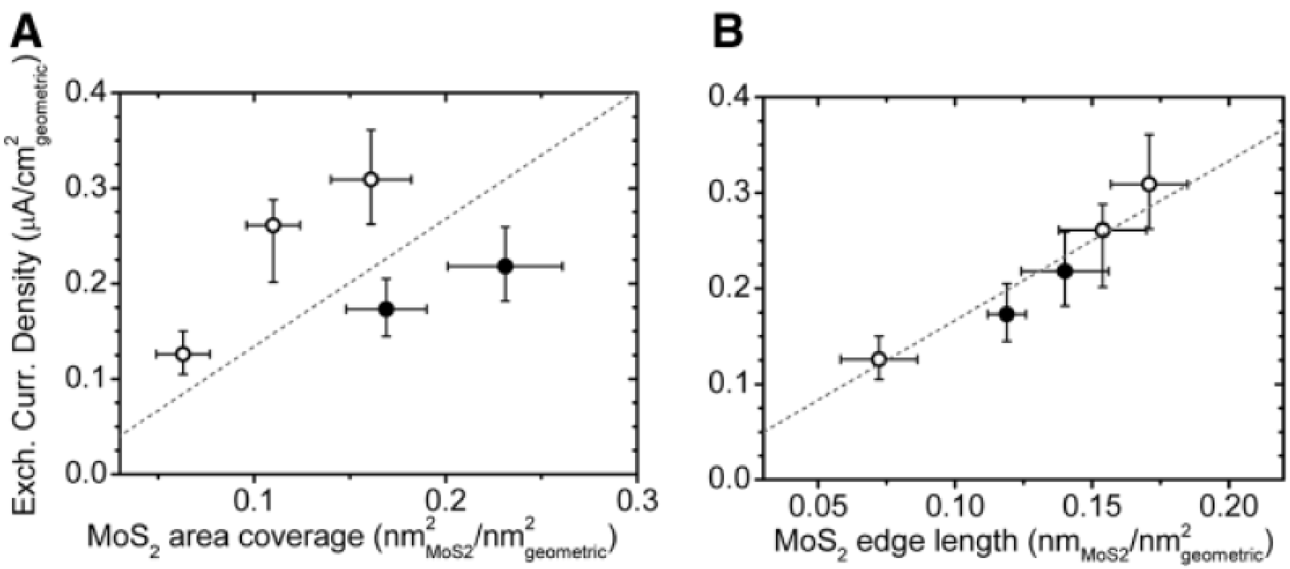
Gambardella Group, Nature, 2002



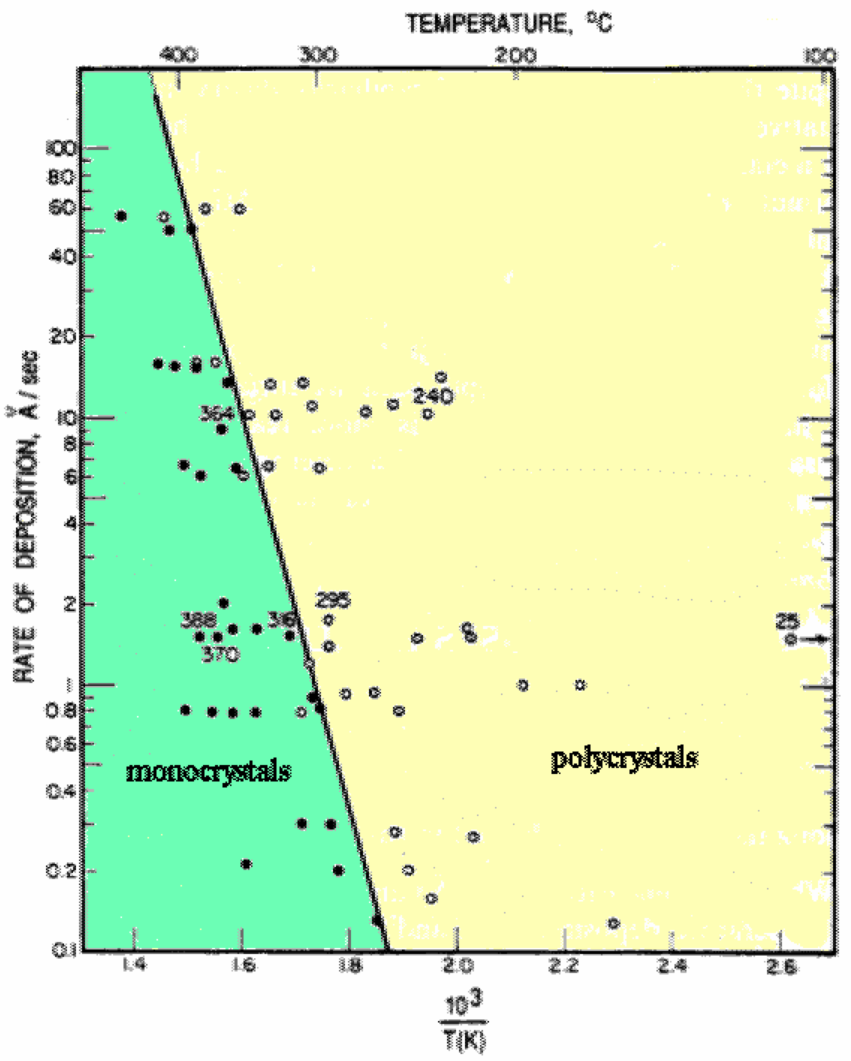
Submonolayer: MoS_2 Edge Hydrogen catalysis



Chorkendorf group, Science, 2007



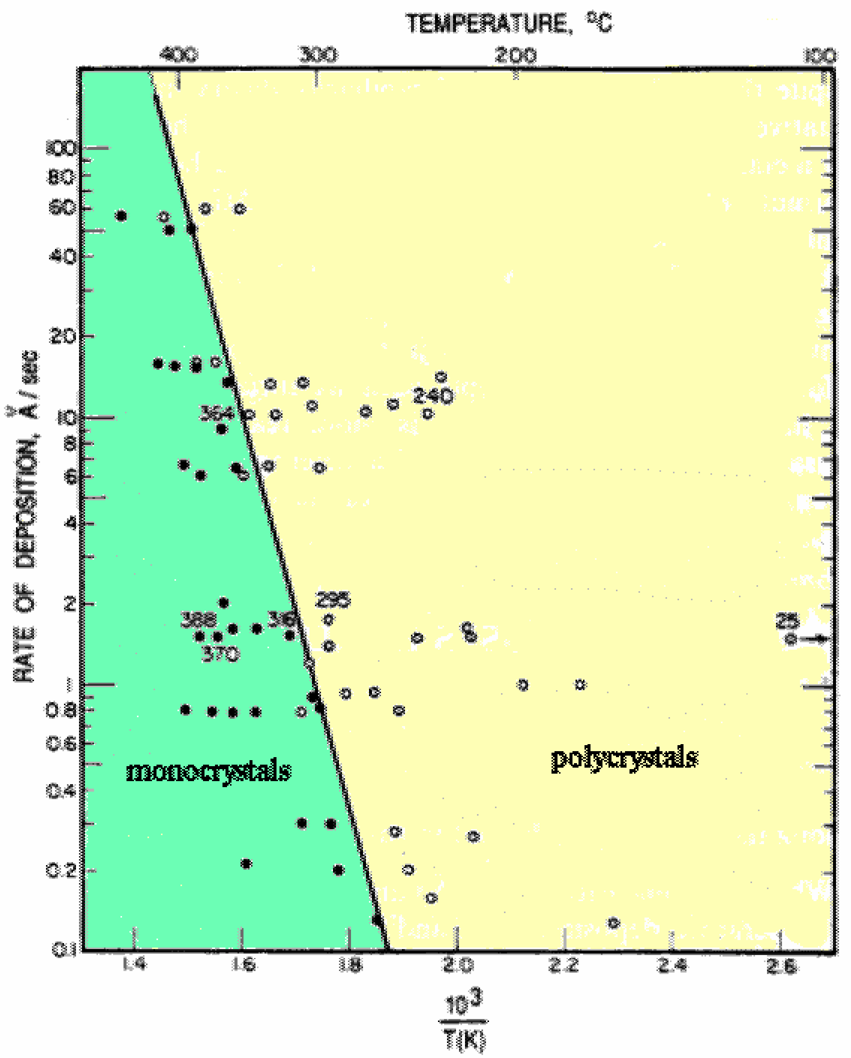
Monolayer: Cu films deposited on (111) NaCl substrate.



Dependence on substrate temperature and deposition rate

- If equilibrium is achieved for all ad-atoms, film will be mono-crystal (epitaxy).
- Higher temperature increases ad-atom's surface mobility. It will stop once it finds the lowest energy position nearby.
- Too fast deposition stops the movement (before the ad-atom finds the lowest energy position nearby).

Monolayer: Cu films deposited on (111) NaCl substrate.



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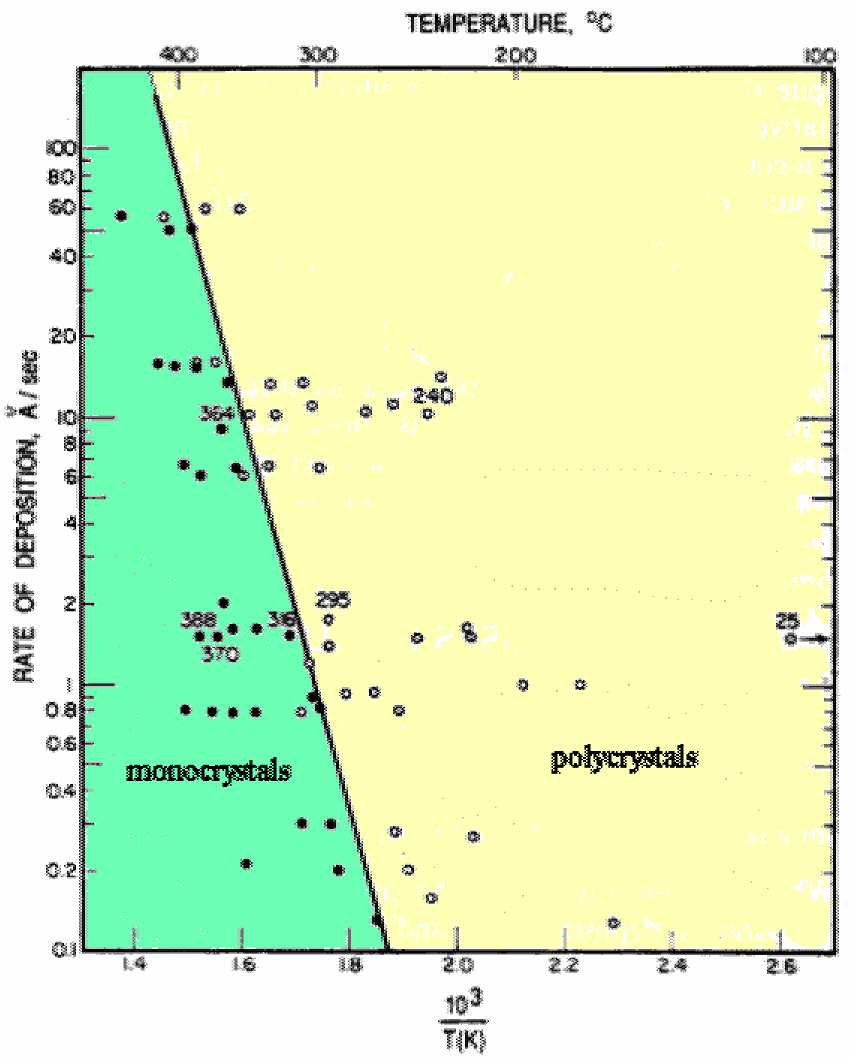
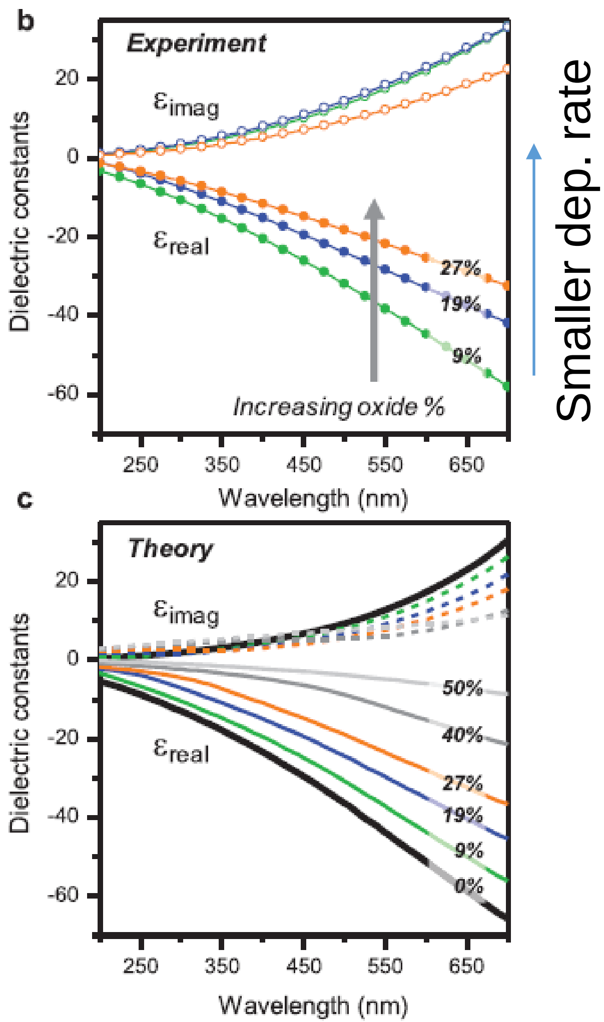
Nordic Nanolab Network

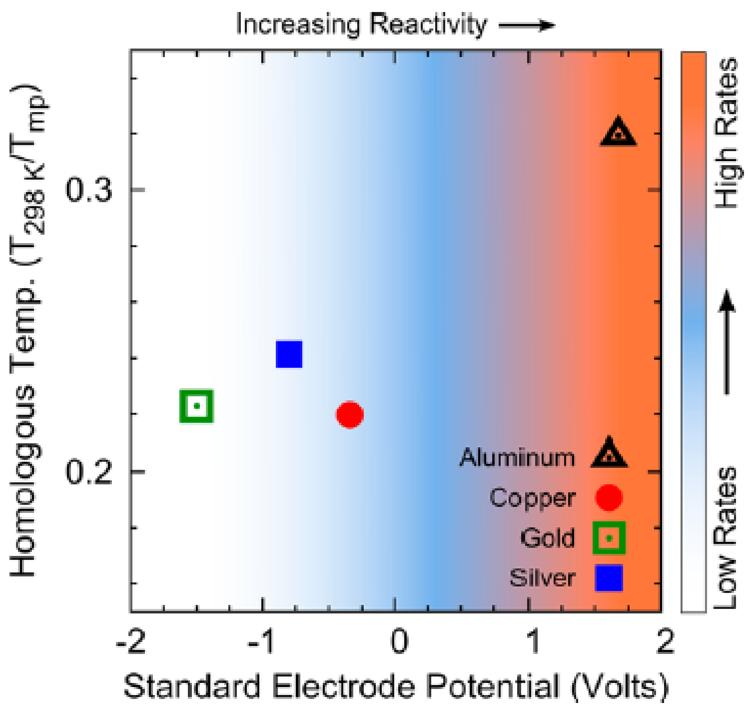
Aluminium on oxide surfaces





Knight et al., ACS nano 2013

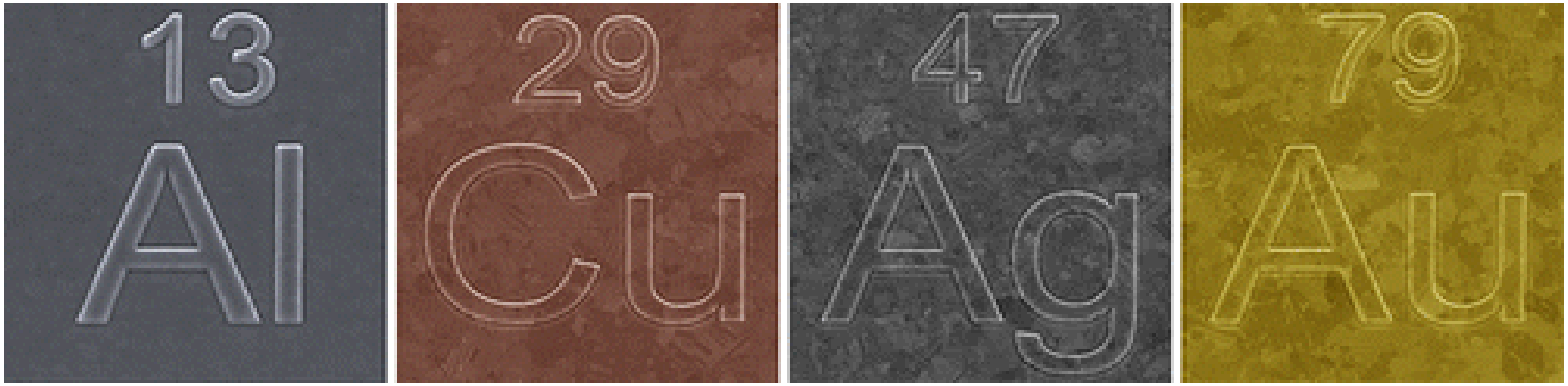
Solution: read old (or new) surface science



- $T_h \sim 0.3$ (assuming T_{sub} is at room temperature).
- $0.15 < T_h < 0.3$ contain metastable phases with surface diffusion-driven grain growth proceeding for the mobile grain boundaries.
- Fast evaportaion rate heat less the substrates!
- Large deposition rate decrease reactivity of the film and improve the optical properties

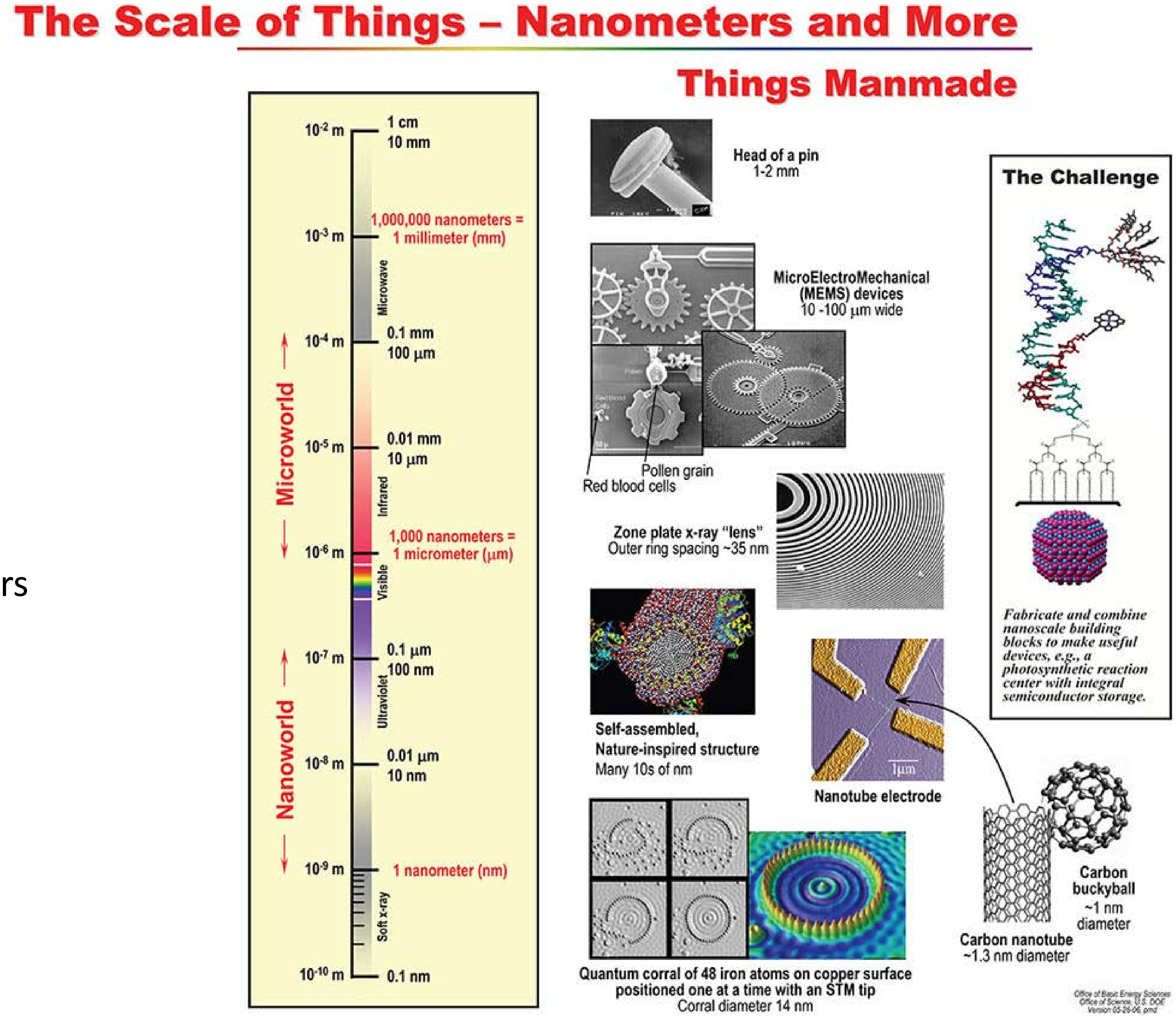
Norris et al., ACS photonics 2015

Take home messages



- Pressure should be as low as possible
- Radiative heating does not influece very much the deposition characteristics
- Rate should be high for reactive metal

Nordic Nanolab Network

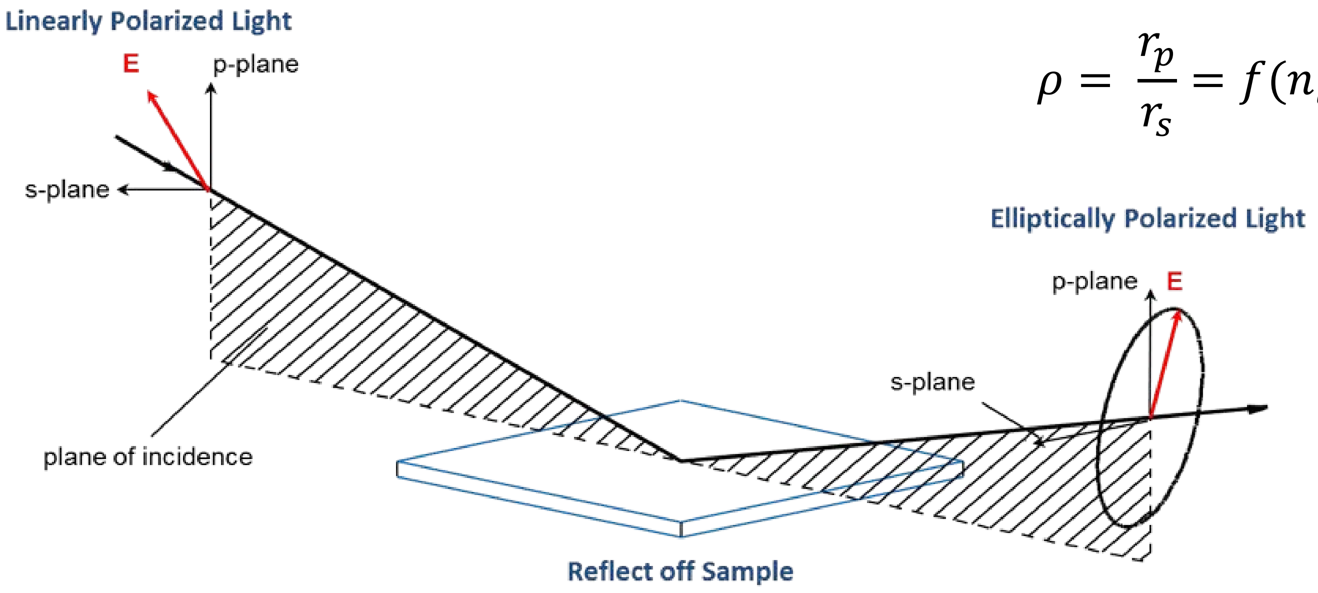


Multilayers

Thin film

Thin film evaporation: characterization

- Grow good quality materials

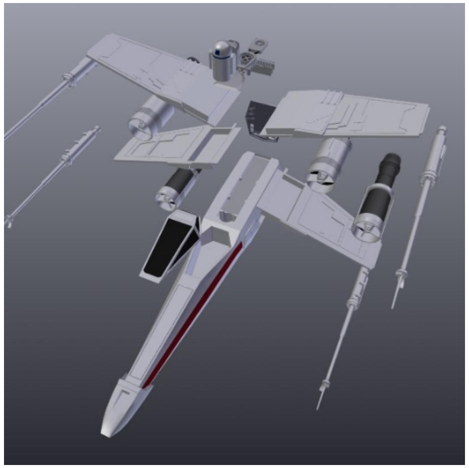


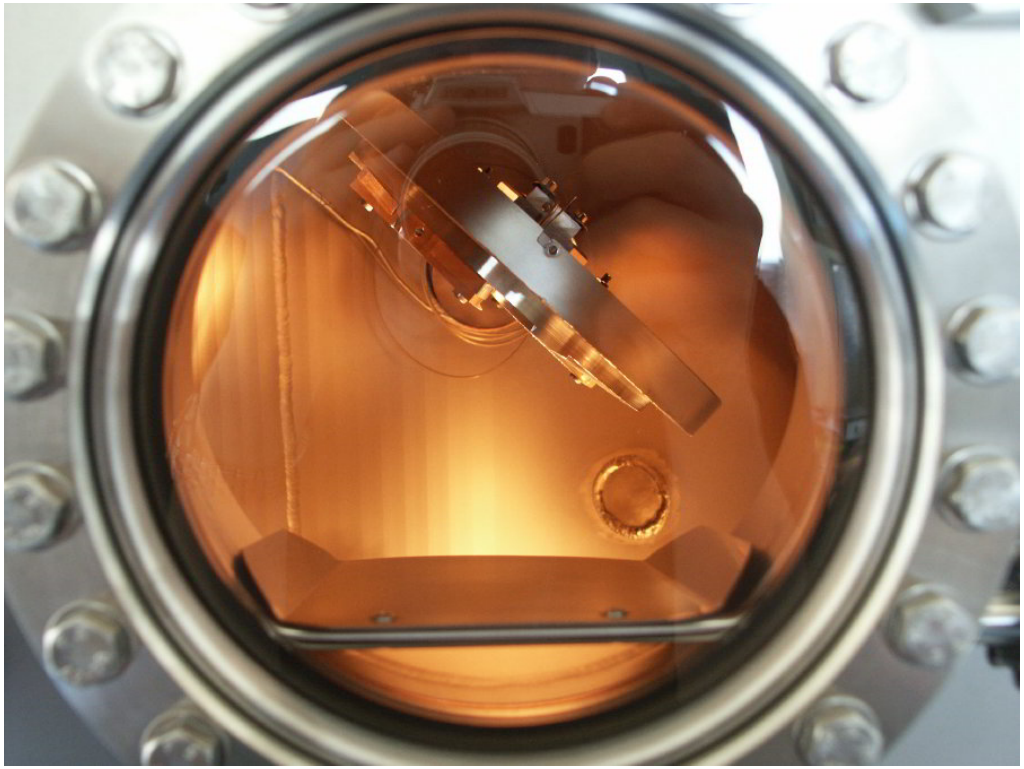
$$\rho = \frac{r_p}{r_s} = f(n_l, d_l)$$

Ellipsometry is non-invasive, and provide ALL required information about the optical properties of a fillm.

Use and report your results in a paper so that comparison becomes straightforward

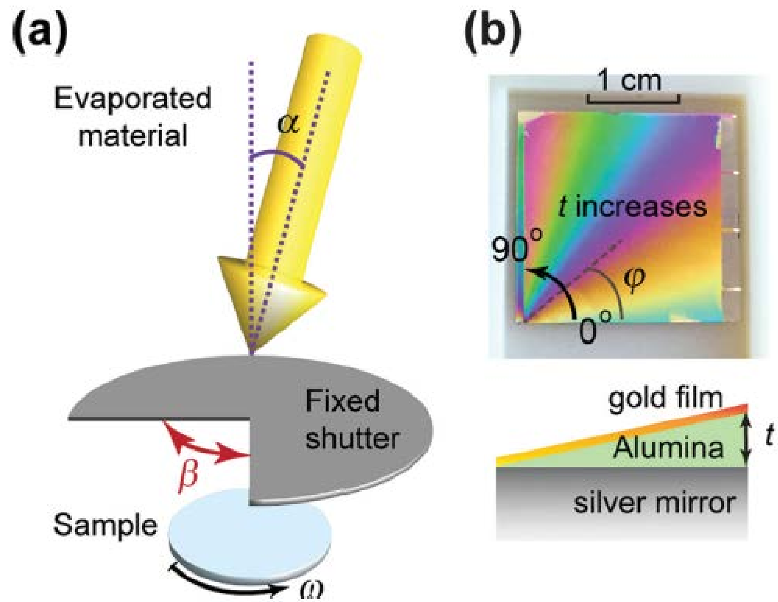
Stage/sample control



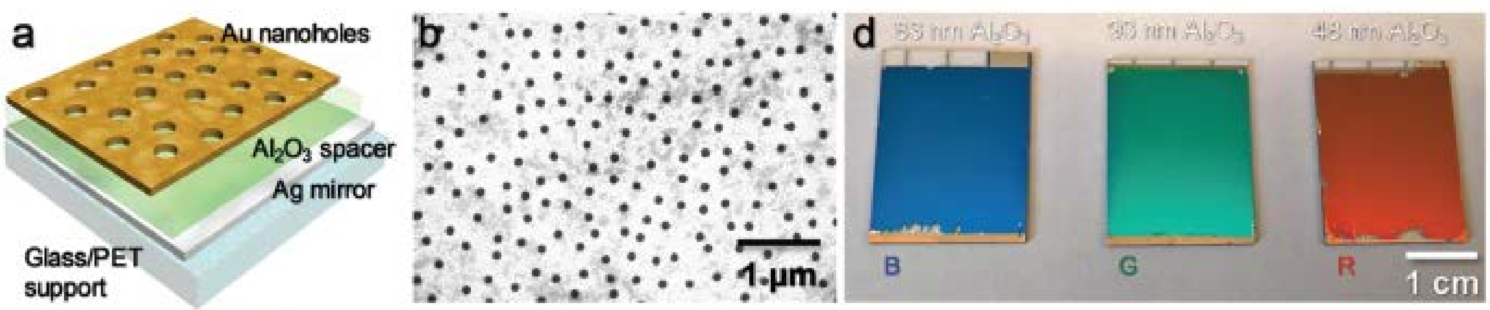


What can one do using rotating and tilting stages?

Rotating stage

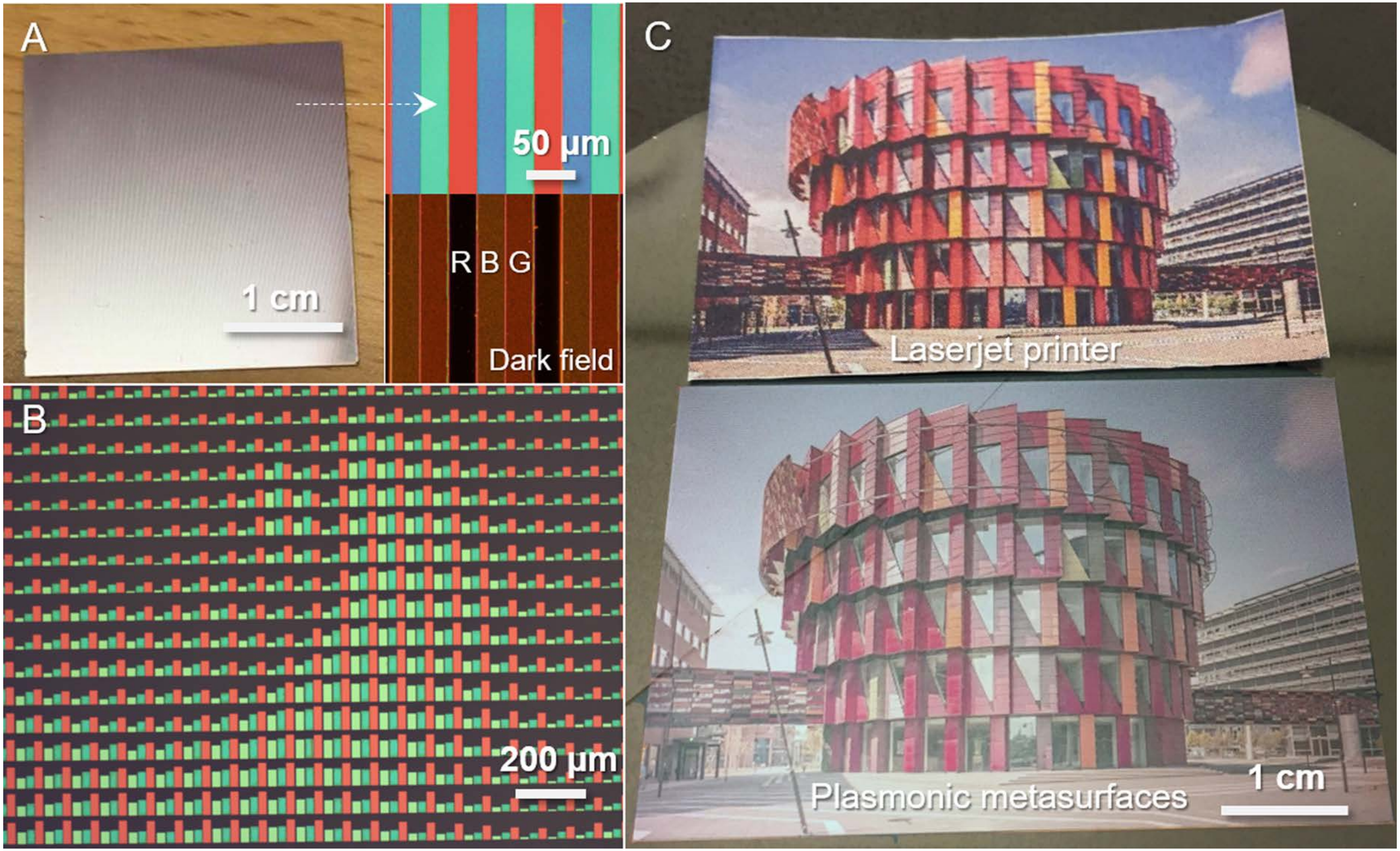


Ogier et al. Advanced materials 2016



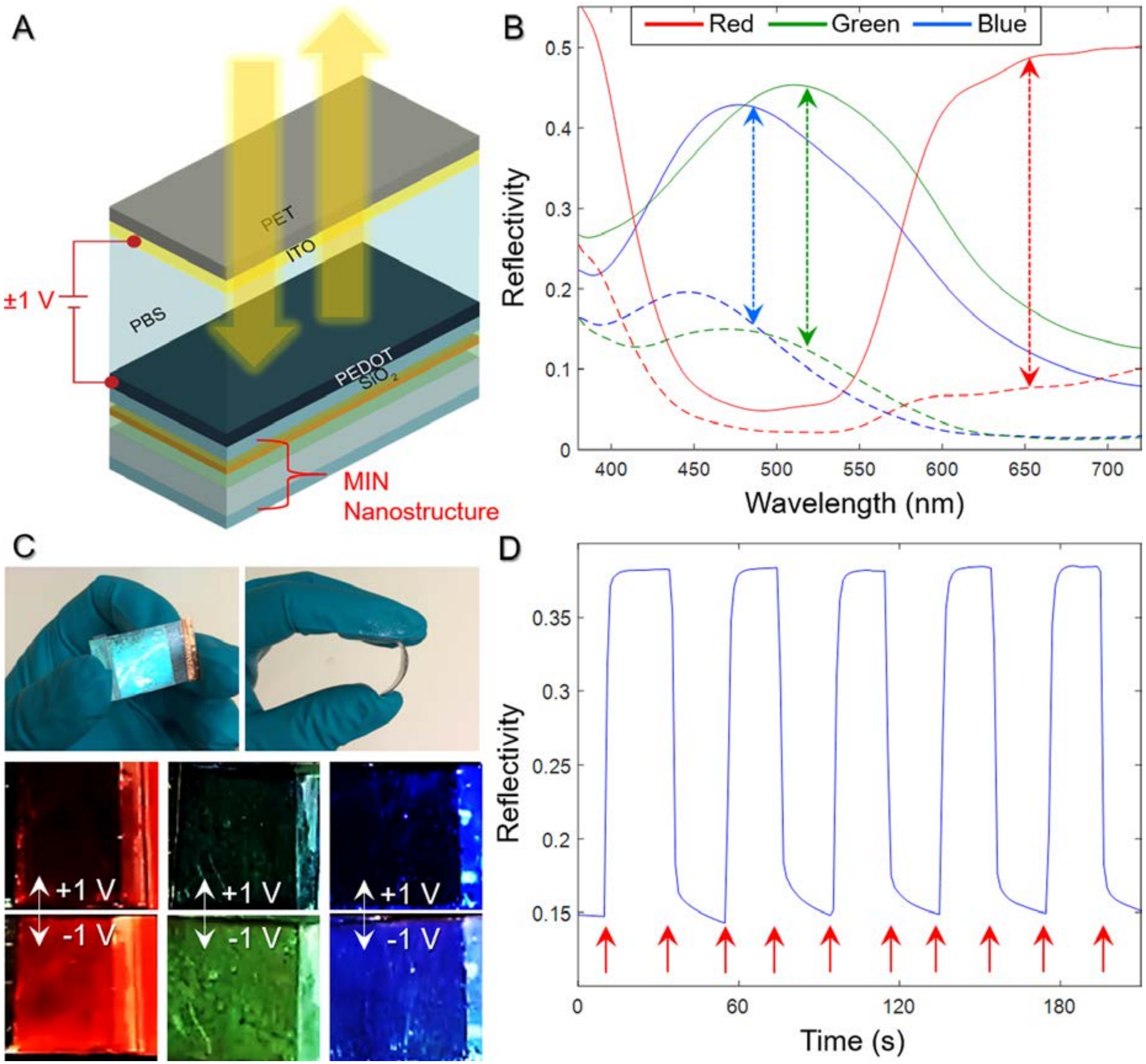
Xiong et al. Advanced materials
Nano Letters

Metallic reflective paper



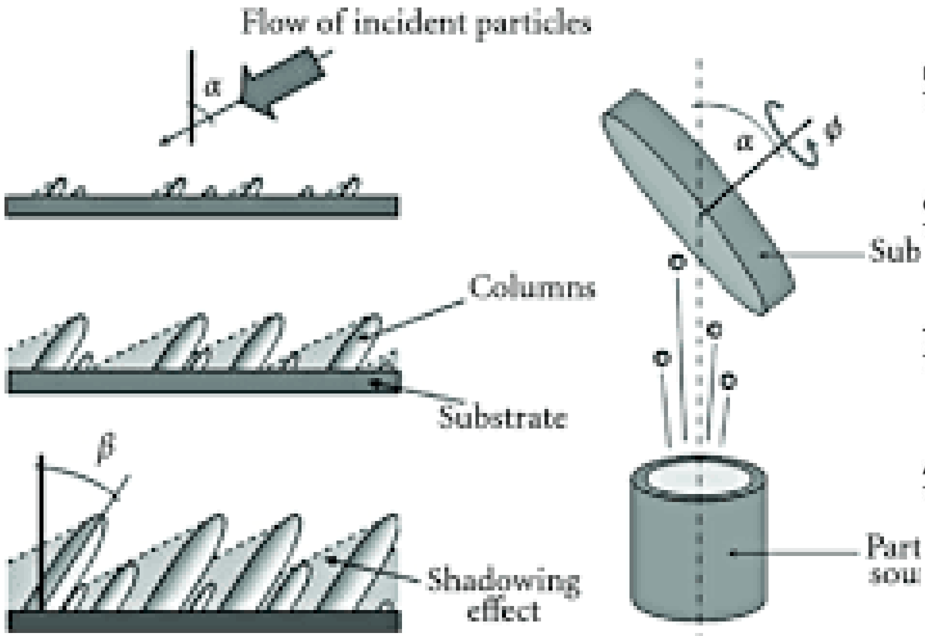
Xiong et al. Nano Letters

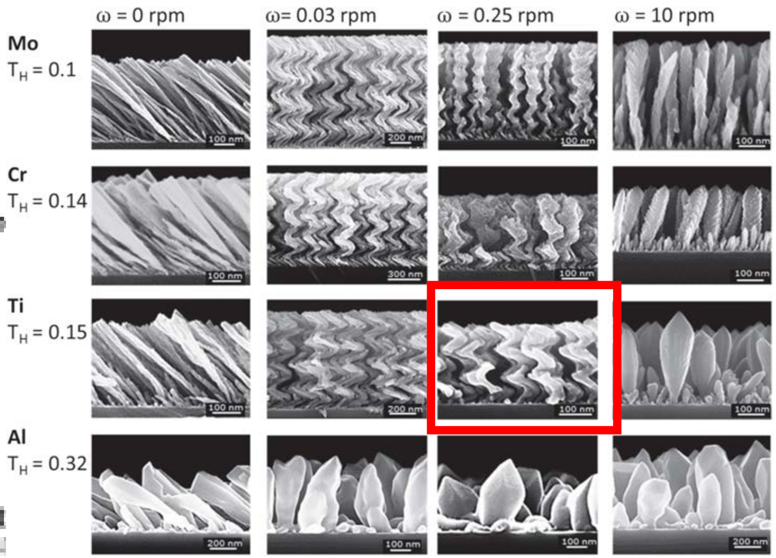
Future coloured Kindle



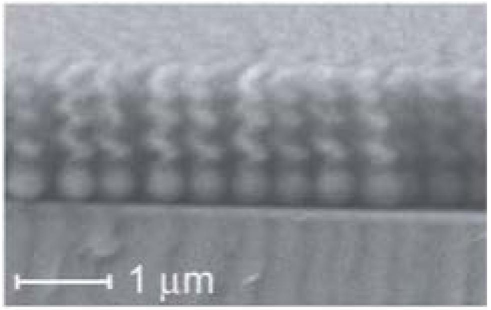
Xiong et al. Nano Letters

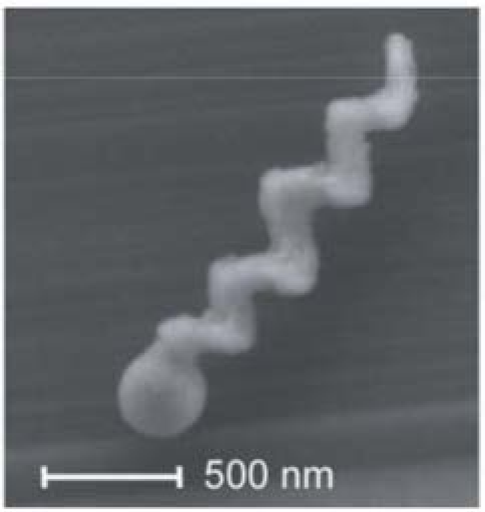
Tilting + rotating stage





Tilting + rotating stage





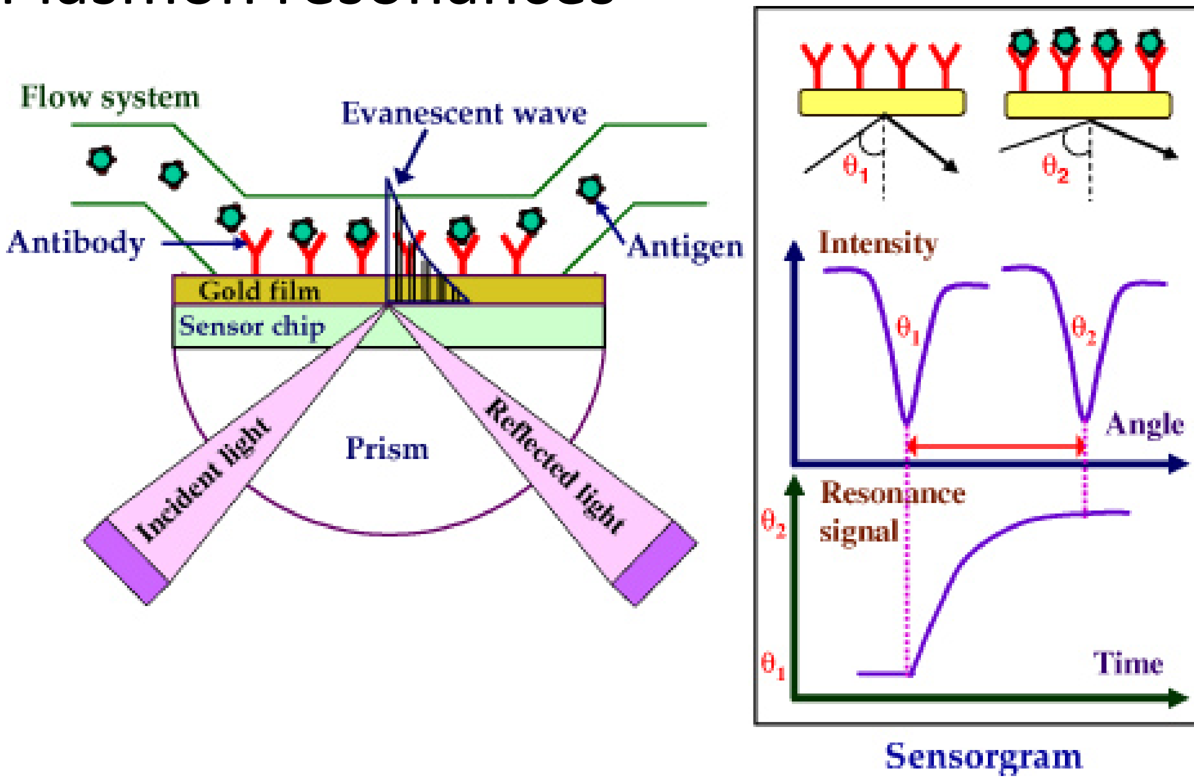
Fisher group

Nelson group, advanced Materials, 2012

Applications

Au film: Surface Plasmon resonances

$$k^2 = \frac{\omega^2}{c^2}\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}$$

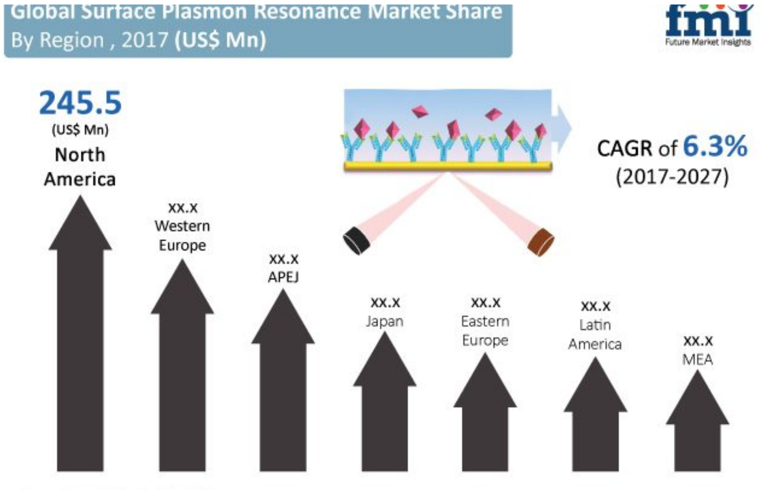


- Label-free
- Sensitive
- Cheap and Simple
- Reproducible

Norio Miura et al., Journal of Physics D: Applied Physics

Nordic Nanolab Network

Au film: Surface Plasmon resonances



Type of Market	World Wide Market Size (M USD)	Year	Growth Rate
Chromatography	$7,000	2015	5.50%
PCR	$4,650	2015	6.60%
Electrophoresis	$1,505	2015	4.80%
SPR/Label-Free	$1,220	2015	**11.86%**
Western Blot	$320	2015	4.00%
ELISA	$141	2015	4.58%

Solar Cooler

Is it possible to create a material which cools down is illuminated by the sun?

Fan group, Nature, 2014

Solar Cooler

Net cooling power is

$$P_{\mathrm{cool}}(T) = P_{\mathrm{rad}}(T) - P_{\mathrm{atm}}(T_{\mathrm{amb}}) - P_{\mathrm{Sun}}$$

- The power radiated by the structure is

$$P_{\mathrm{rad}}(T) = A \int \mathrm{d}\Omega \cos\theta \int_0^\infty \mathrm{d}\lambda I_{\mathrm{BB}}(T,\lambda)\epsilon(\lambda,\theta)$$

- The absorbed power due to atmospheric thermal radiation

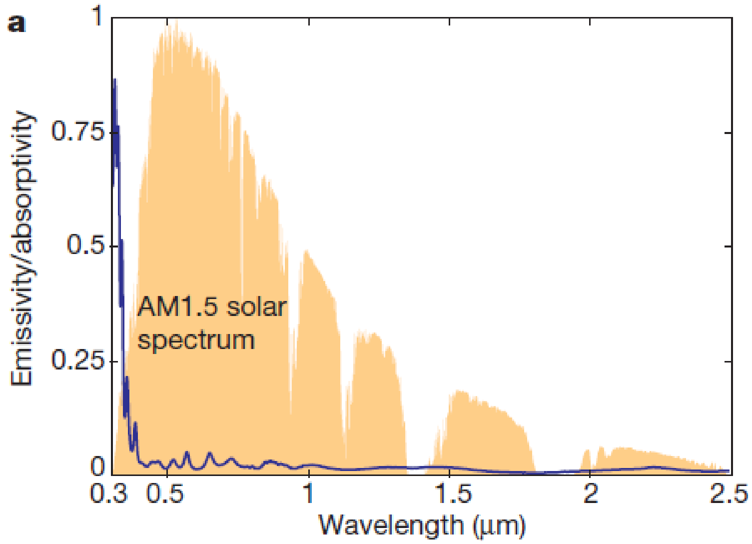
$$P_{\mathrm{atm}}(T_{\mathrm{amb}}) = A \int \mathrm{d}\Omega \cos\theta \int_0^\infty \mathrm{d}\lambda I_{\mathrm{BB}}(T_{\mathrm{amb}},\lambda)\epsilon(\lambda,\theta)\epsilon_{\mathrm{atm}}(\lambda,\theta)$$

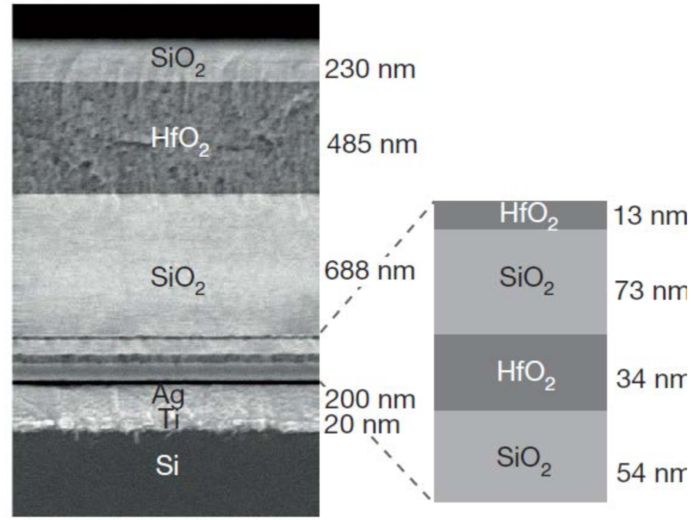
- The absorbed solar power absorbed by the structure

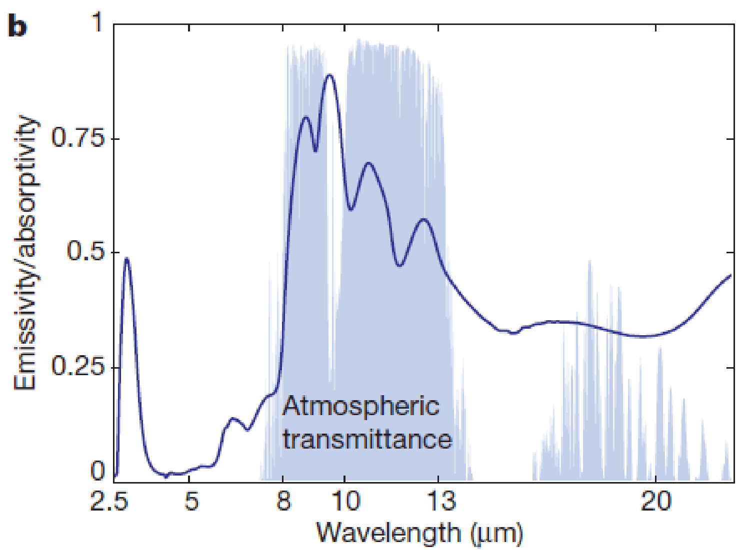
$$P_{\mathrm{Sun}} = A \int_0^\infty \mathrm{d}\lambda \epsilon(\lambda,\theta_{\mathrm{Sun}})\, I_{\mathrm{AM1.5}}(\lambda)$$

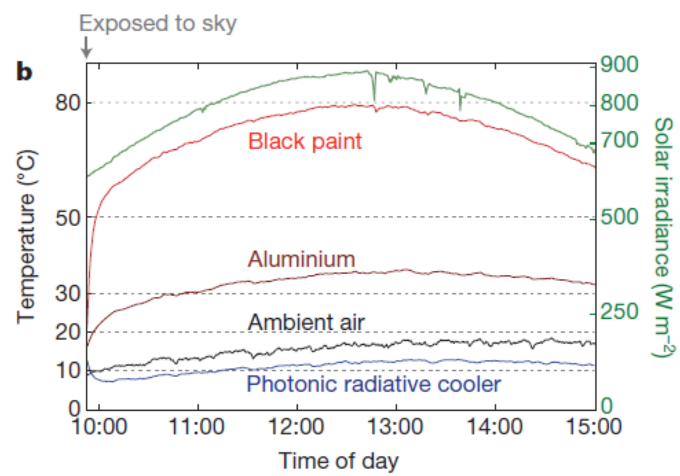
94% of sunlight must be reflected

Solar Cooler

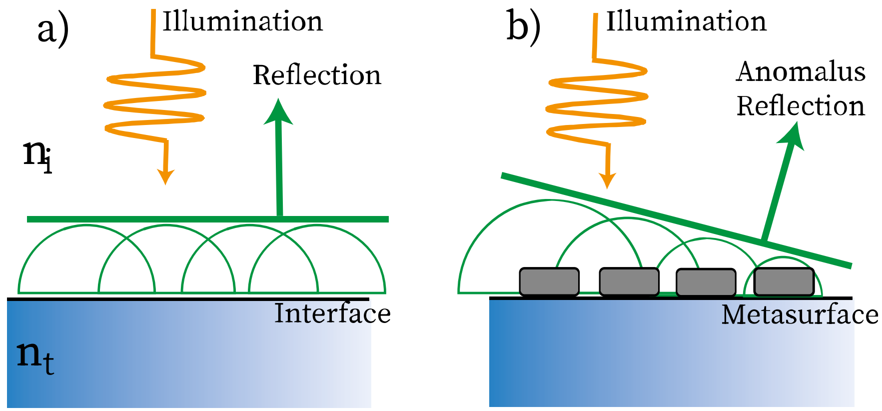






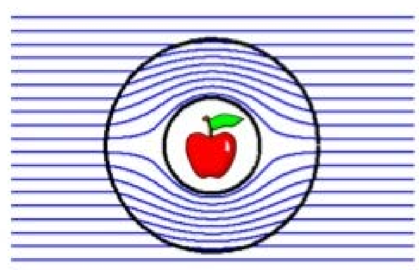


Metasurfaces: a new way to control light



holograms

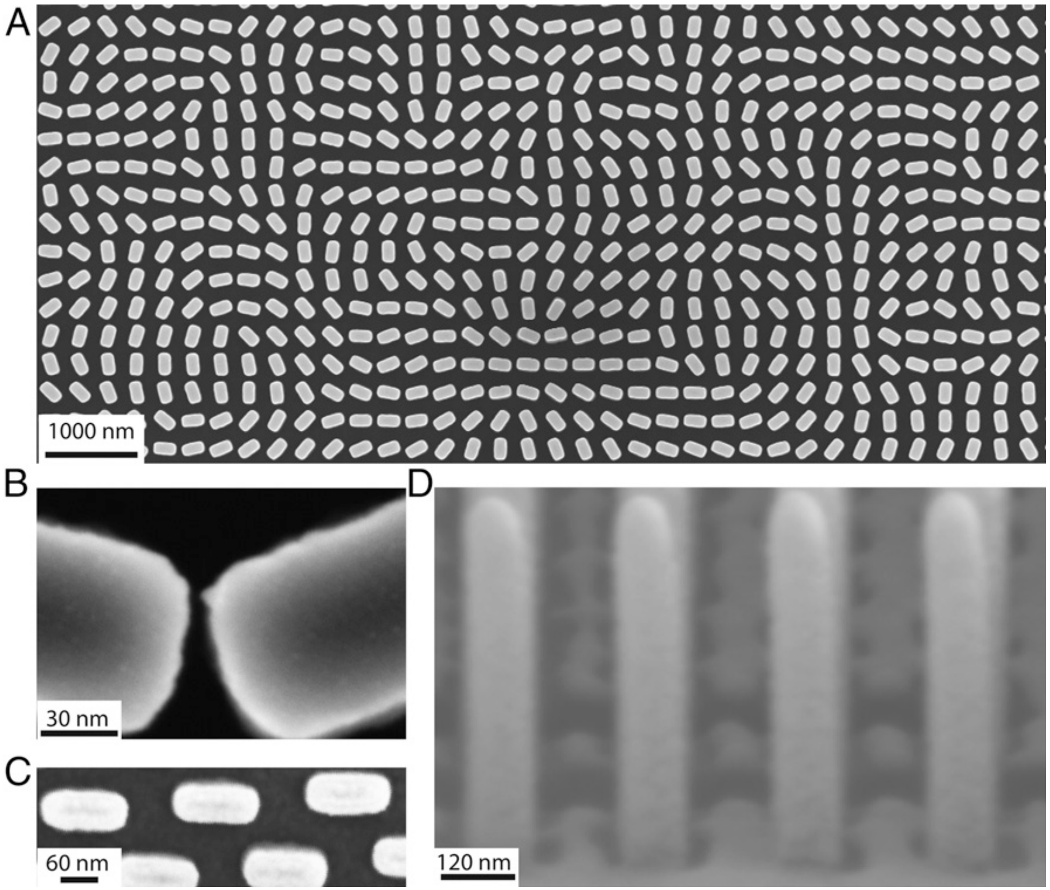
Invisibility cloak

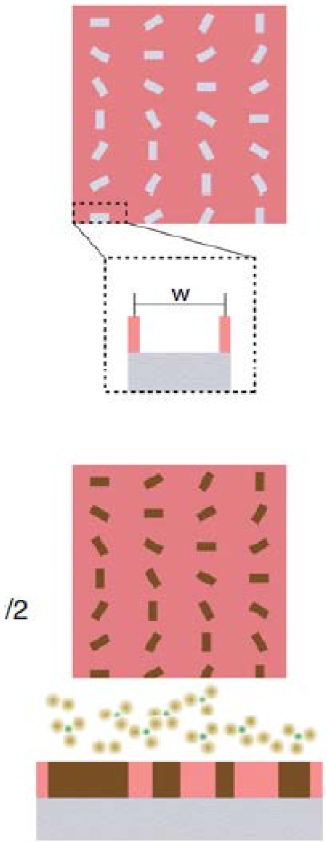


light deflection

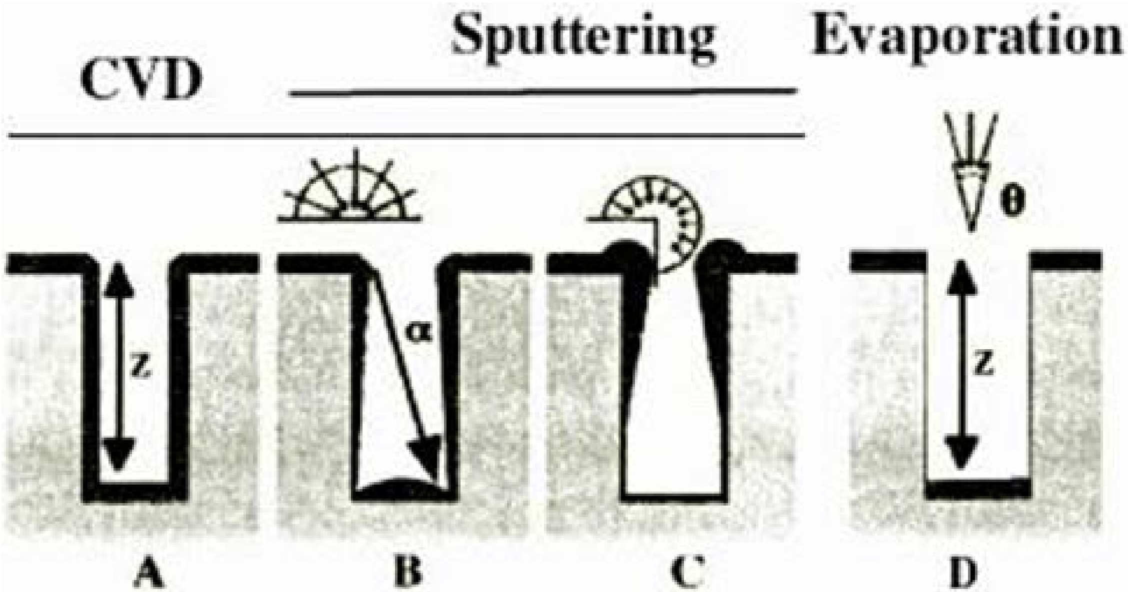
Lenses of phones

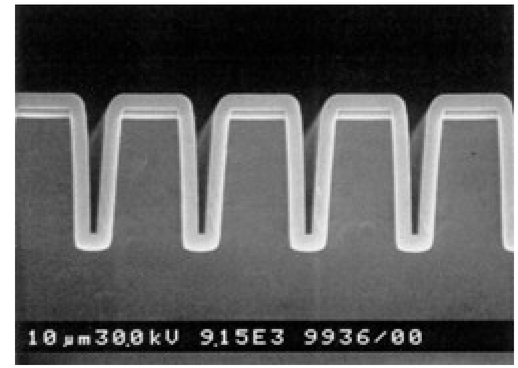
Metasurfaces: a new way to control light



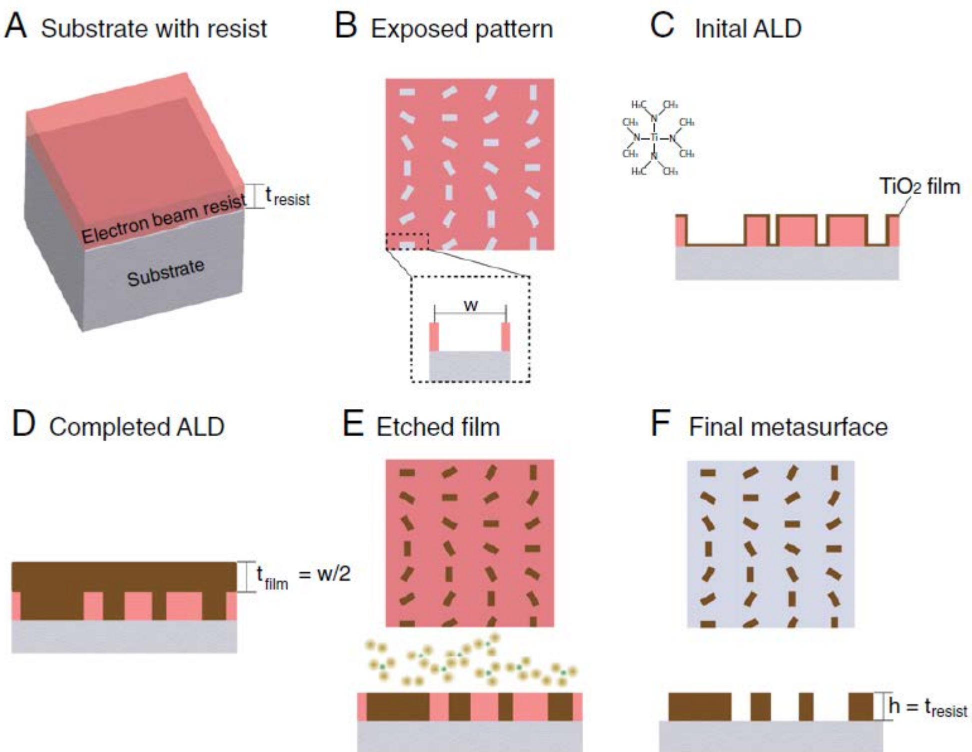


Metasurfaces: a new way to control light

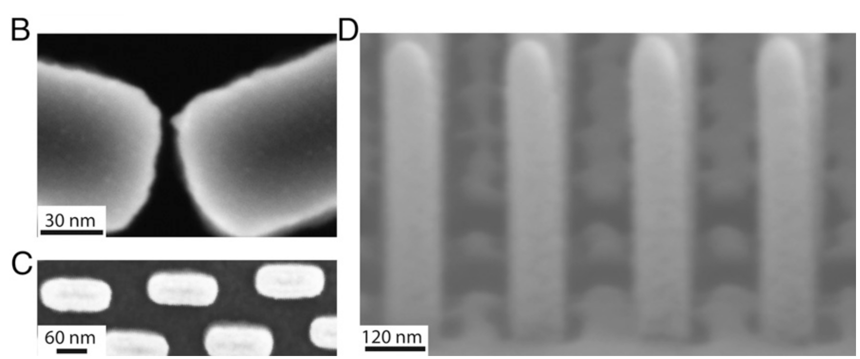




Metasurfaces: a new way to control light



Capasso group, Science, PNAS



Coating in particle physics

LHC in CERN:

- Decreases electron clouds
- In LHC the walls are covered by a thin a-C layer deposited by sputtering.
- They used the superconducting magnet to induce the plasma and sputter

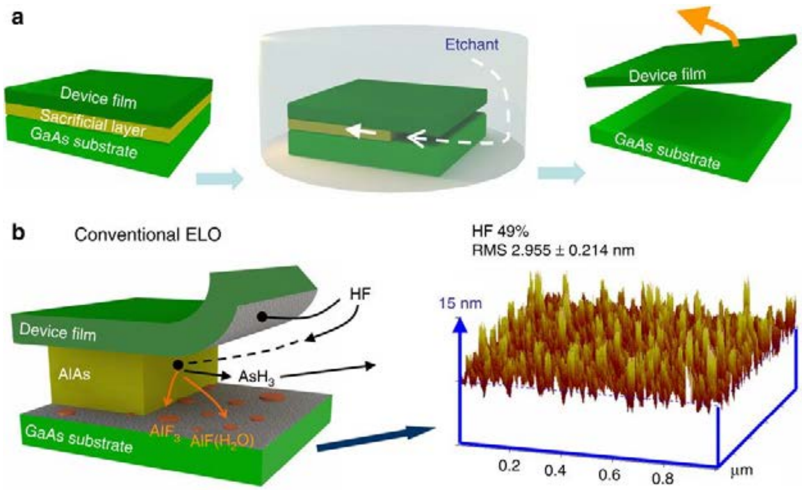
https://cds.cern.ch/journal/CERNBulletin/2014/07/News%20Articles/1645428?ln=en

Beer and Festivals: further upscaling

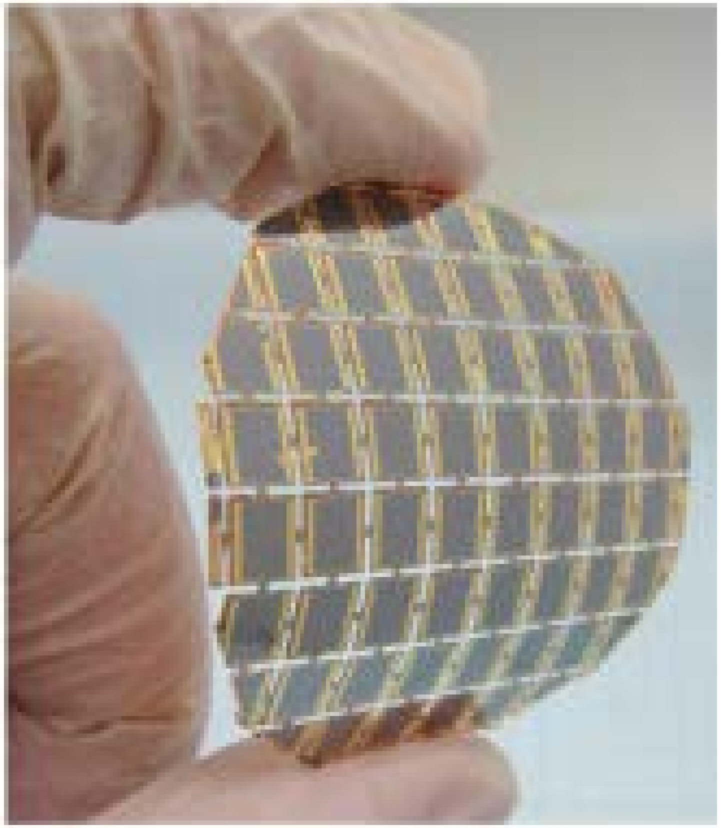
Light and energy: solar impulse 2

Capacity	1 pilot
Wingspan	72 m
Weight	2.3 tons
Number of solar cells	17,248
Number of propellers and batteries	4
Total energy produced from Abu Dhabi to Abu Dhabi	11655 kWh
Maximum flight time achieved	117 hours 52 minutes (André Borschberg)
Maximum altitude	28,000 feet
Average airspeed	75 km/h
Maximum recorded ground speed	216 km/h

Epitaxial layer lift-off



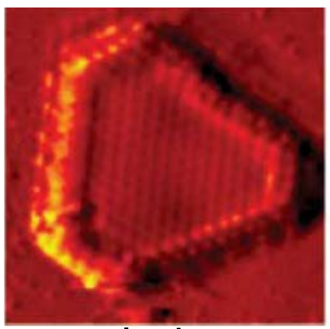
Sadana group, Nature Comm. 2016



Fan-LeiWu et al.,
Solar Energy Materials and Solar Cells, 2014

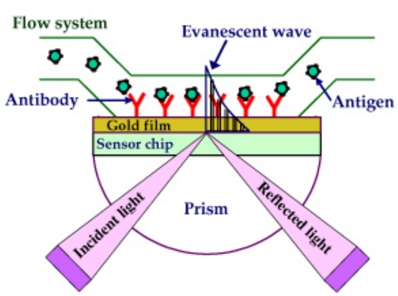
Conclusions

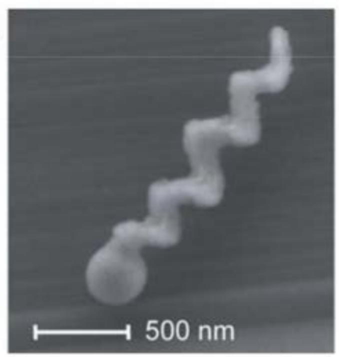
- We need to grasp how machine are working if we want to use them (often Wikipedia is enough)
- Thin film deposition is an active area of research where multiple applications can be found and findamental questions can be answered
- Examples:



Catalysis

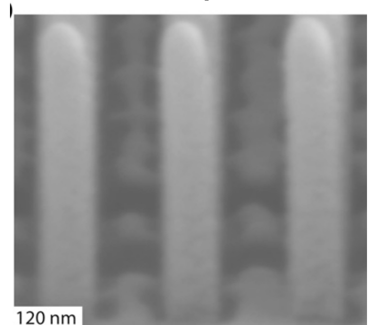
Biology





Active matter

Meta-optic



Energy

Thank you for your attention and good research

Vetenskapsrådet

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AVANCEZ 1829

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