Nanostructure Fabrication:

Challenges of Top-Down and Bottom-Up Approaches

A view of the application landscape

And a selective and personal view of the underlying fabrication technologies

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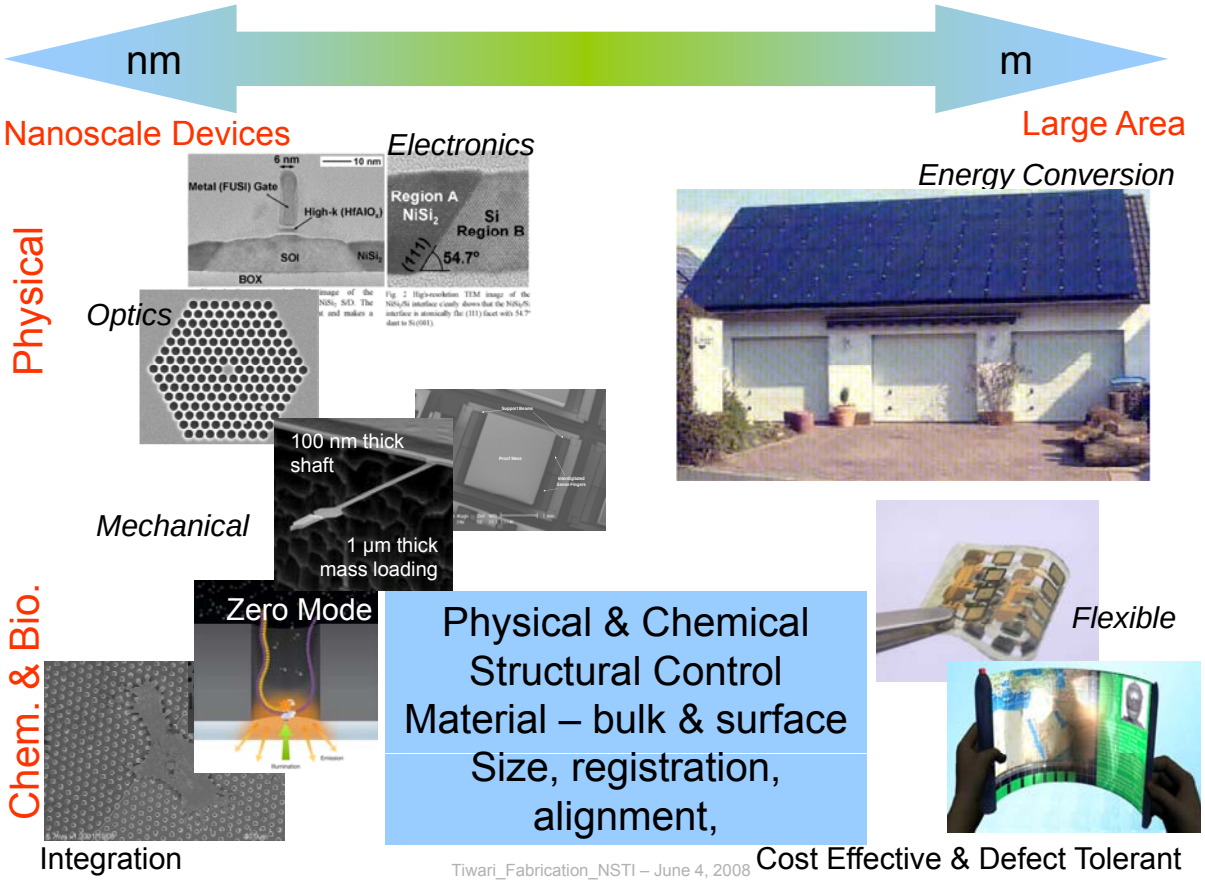


Complexity of Fabrication: Three-Dimensional Electronics

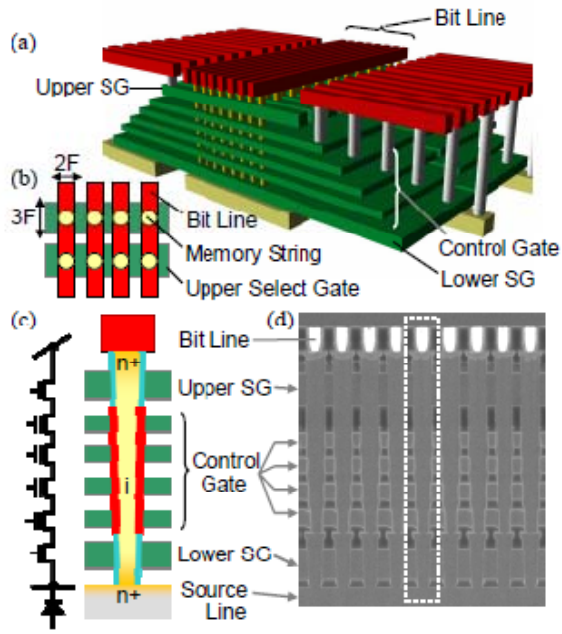


Figure 1: (a) Birds-eye view of BiCS Flash memory. (b) Top-down view of BiCS Flash memory array. (c) Enlarged view of the memory string. (d) Cross sectional SEM image of BiCS Flash memory array.

Y. Fukuzumi et al., IEDM(2007)

FLASH

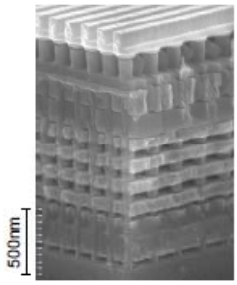
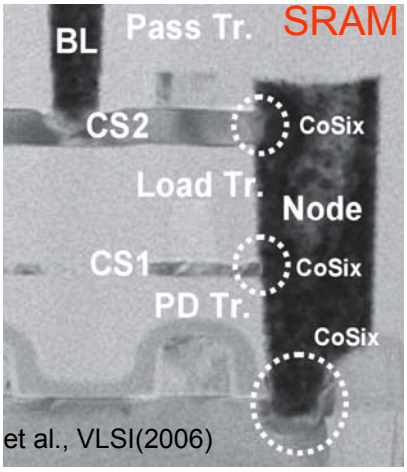


Figure 16: Birds-eye view SEM image of BiCS Flash memory.

SRAM



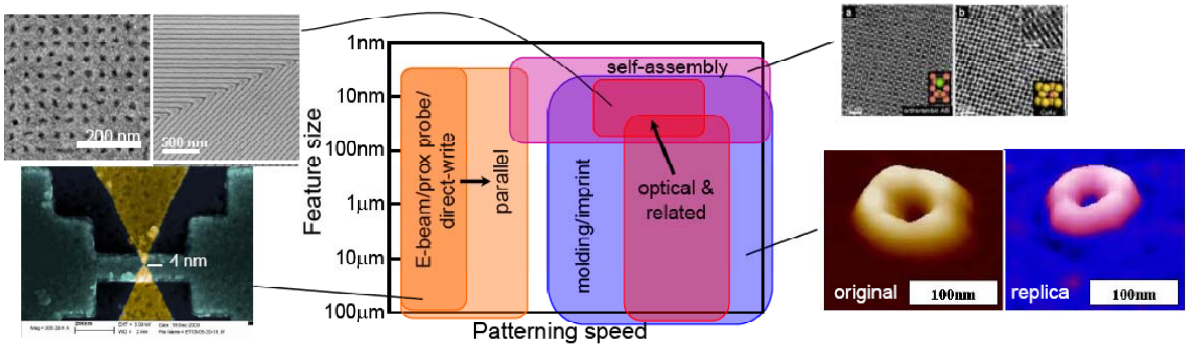
SM Jung et al., VLSI(2006)

Fabrication?

Assembly of Materials
Patterns: Lithography and Self Formed
Pattern Transfer: Removal or Addition using solid, liquid, gas, plasma
Materials Interactions during formation and in use
…

- I would like to explore with the following perspective:
  - What are the applications and their needs?
- What are the characteristics of the technologies that we have?
- Therefore, what is likely to find a good match? And what are the challenges to the technology

Approaches



A third scale on this graph should be defect rate; it also affects the potential area of use

Pattern Formation: Lithography etc.

Photons
- UV, DUV, EUV, XRays
  - Diffraction and Depth of Focus

Charged Particles
- Electrons and Ions
  - Serial writing and Small area

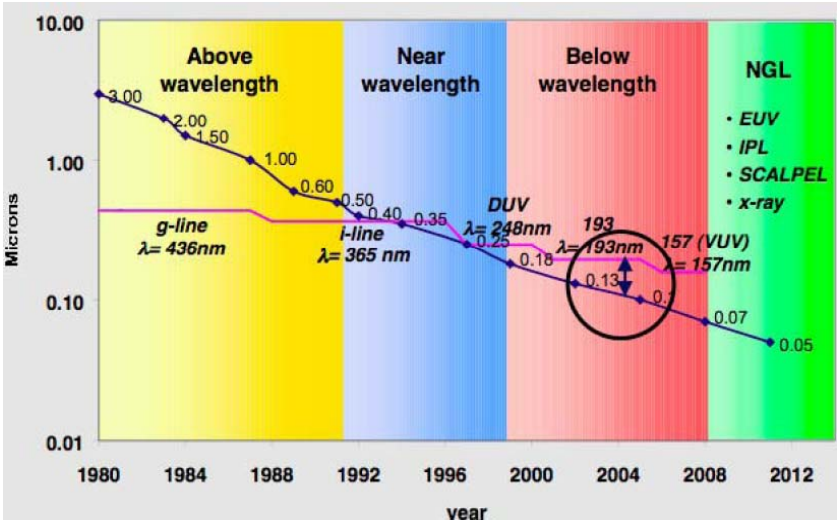
Physical Contact
- Printing, Molding and Embossing
  - Adhesion at contact and pattern transfer flow

Edge-Based
- Near field phase shifting and topographic approaches
  - Diffraction

Deposition
- Shadow Evaporation
  - Low flexibility

Self Assembly
- Surfactant systems and Block Copolymers
  - Order control and density of defects

Photons

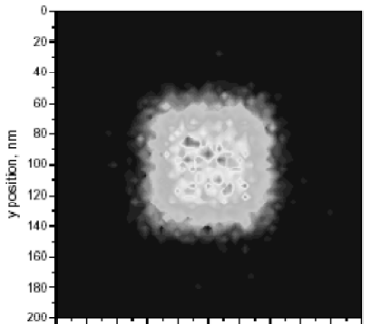


Approaches:

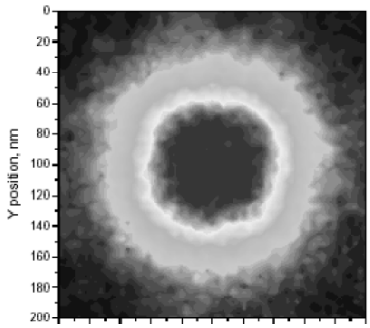
130 nm: Attenuated phase shift, Model-Based OPC
90 nm: Alternating phase shift
65 nm: Sub-resolution assist feature
45 nm: Restricted design rules, Immersion lithography

Photons - Discreteness

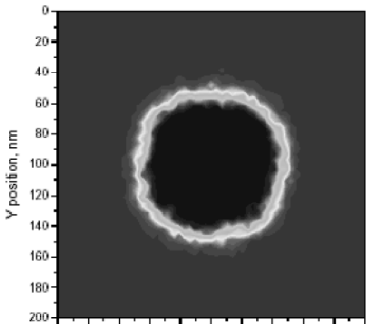
Photons absorbed



Deprotected polymer



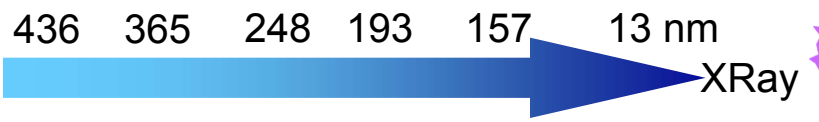
Disolved polymer

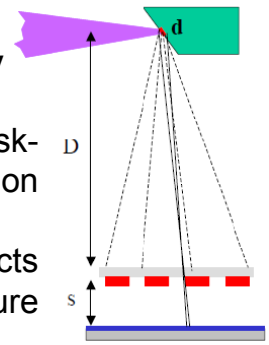


MC simulation of 80 nm contact hole in EUV

J. Cobb, Proc. SPIE

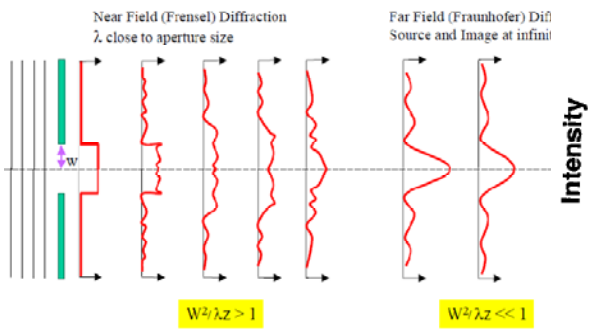
Photons

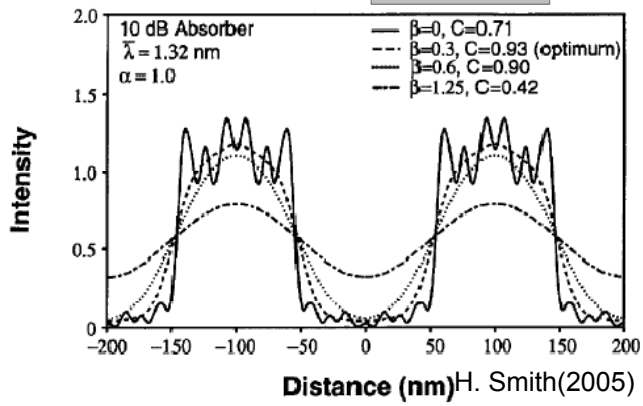




XRay: Resolution limited by λ, mask-wafer gap and Xray generation

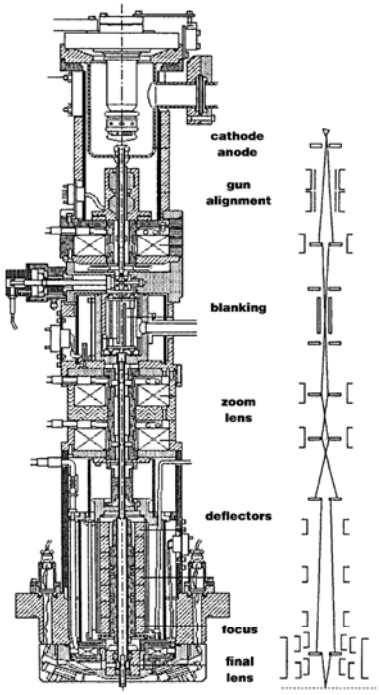
Largely free of thin film effects but difficult infrastructure

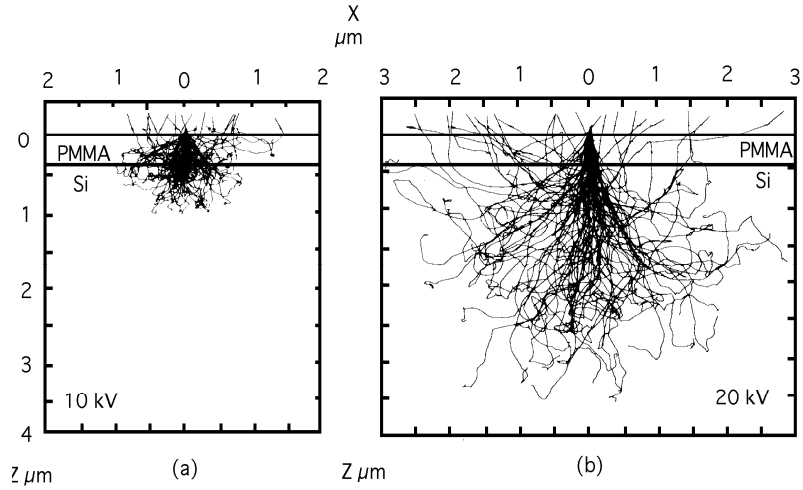




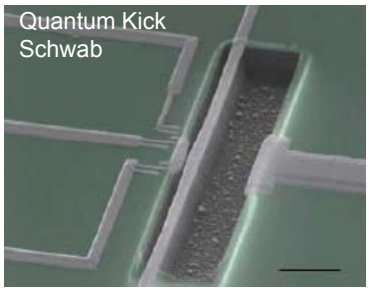
H. Smith(2005)

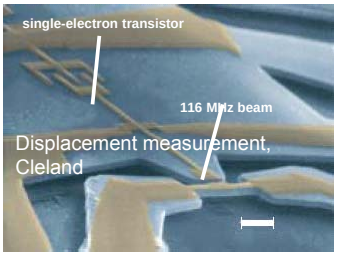
Charged Particles: Electron Beam Lithography



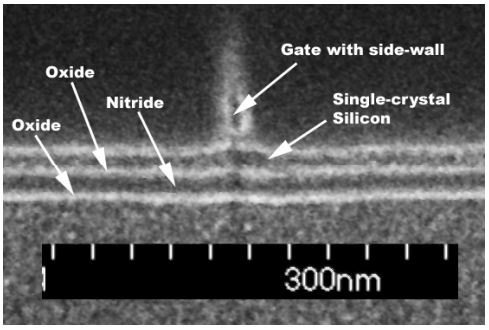


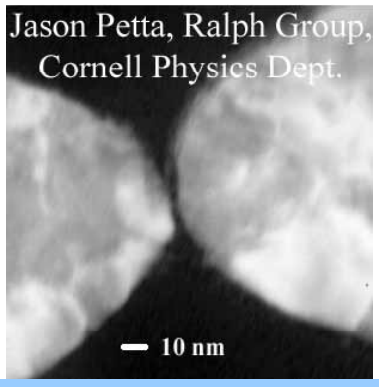
Electron-Beam Lithography





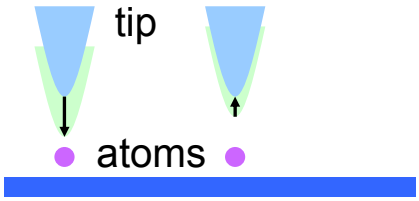
Memories & Transistors

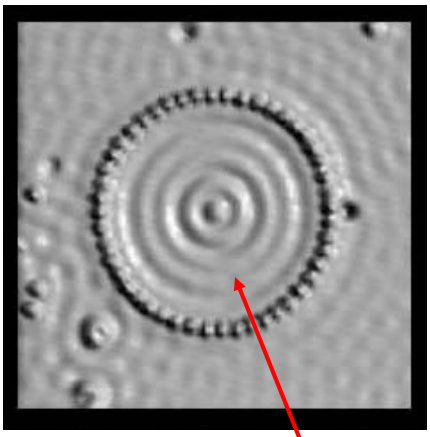


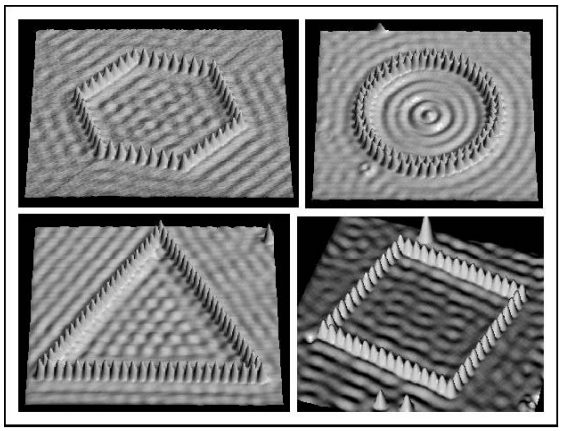


Most interesting working examples at nanoscale, but slow

Scanned Probe: Atom by Atom



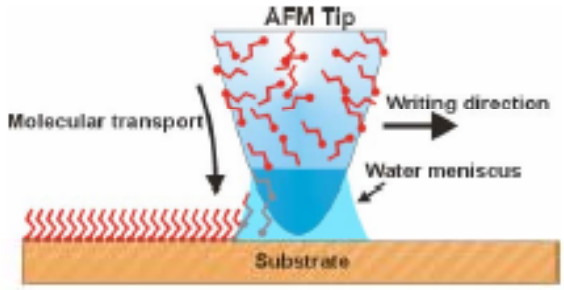




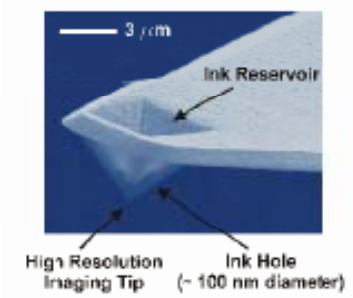
D. Eigler, IBM Almaden

note waves

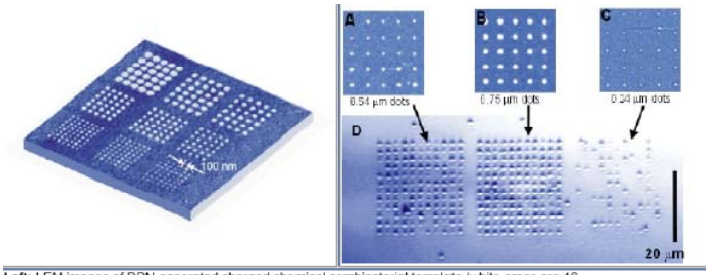
Scanned Probe Techniques: Dip Pen



Piner et al., Science (1999)



Adeyeye, (2006)

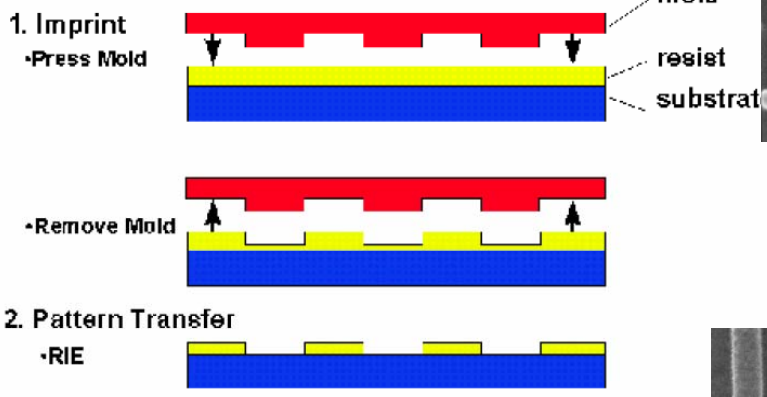


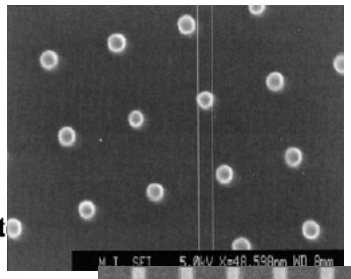
Left: LFM images of DPN generated charged chemical combinatorial template (white areas are 16-mercaptohexadecanoic acid and dark areas are 18-octadecanethiol) for studying assembly of charged particles. **A, B, and C:** LFM images of MHA template patterns on a gold thin film prior to particle assembly. **D:** an optical micrograph of 930 nm diameter amine-modified polystyrene particles selectively adsorbed to the MHA regions of the substrate.

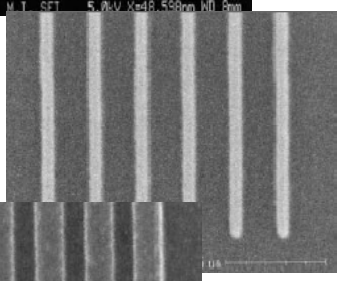
Ivanisevic et al.,
J. Am. Chem. Soc., 2001

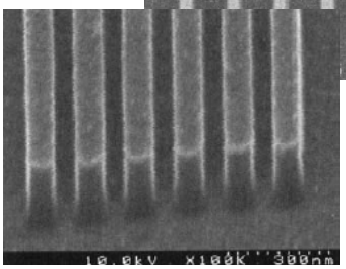
Ink Jets?

Thermal NanoImprint



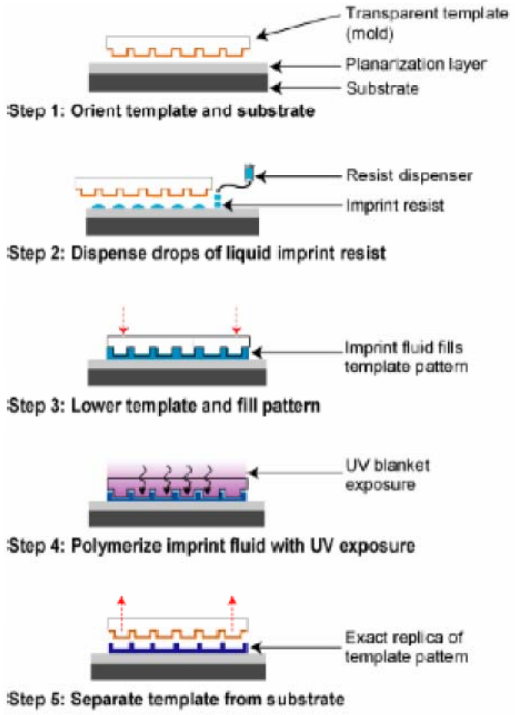






MOSFETs?, TFT, Microfluidics

Ultra-Violet NanoImprint



Lower forces: 100 kPa instead of 500-5000 kPa
No heating, no cooling
Longer lifetime, faster imprint
Sub 5-nm demonstrated

But,
Production of templates
Defect control
Small throughput
Range of materials: high-quality solid-state

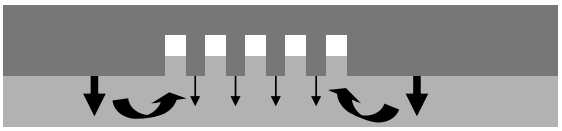
A) Bulk substrate

B) Thin film

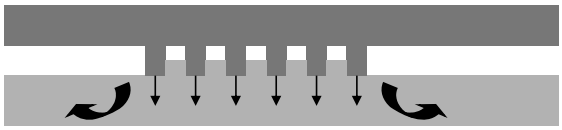
Several levels and back side alignment are possible

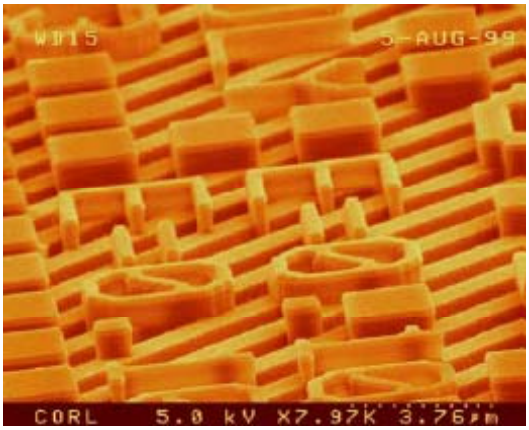
- The stamp geometry defines the flow pattern the substrate undergoes.

Negative Master

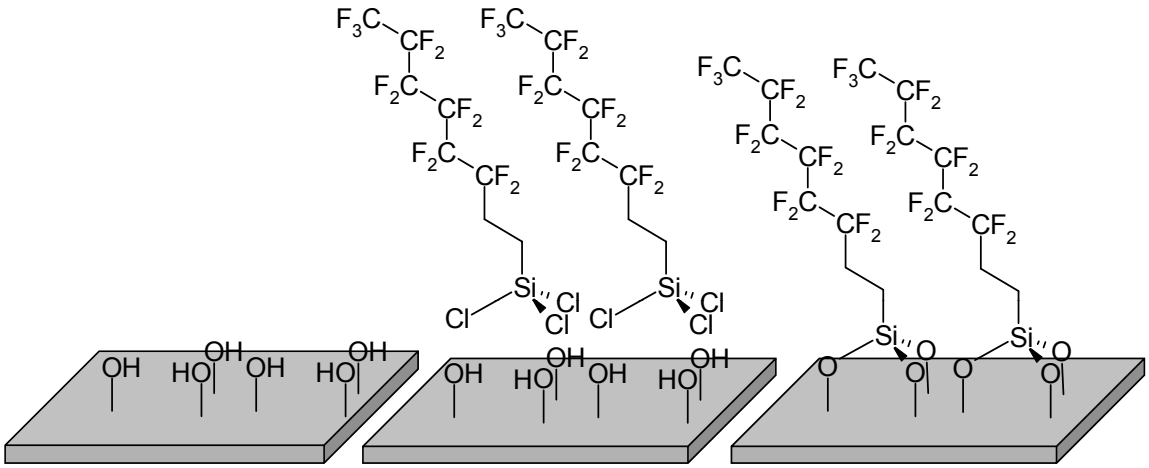


Positive Master





Colburn., SPIE (2000)



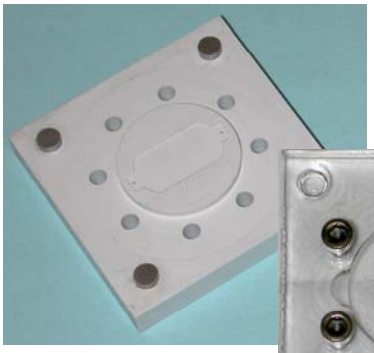
Hydroxylated surface

Hydroxylated surface in presence of silane

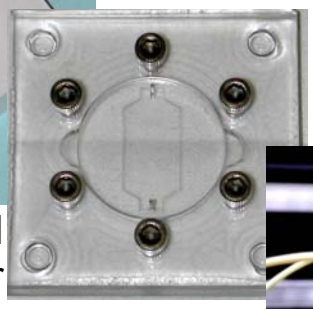
Fluorosilanized surface

Contact: Avoiding sticking?

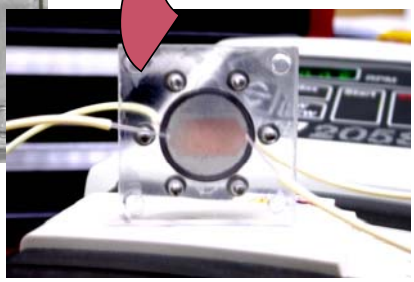
Biology Applications

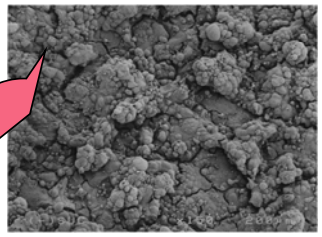


CNC machined master



Embossed and assembled device

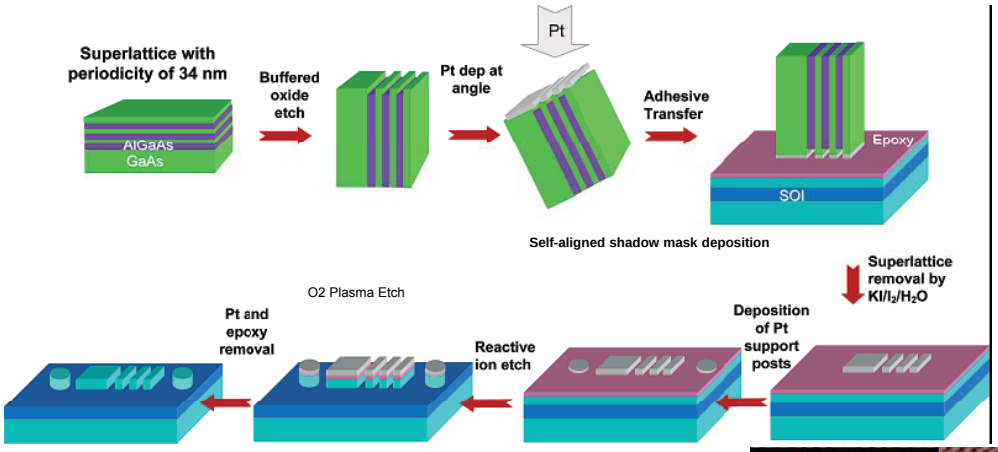


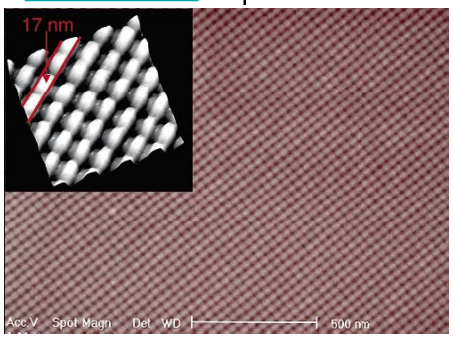


Caco-2 cells growing on a membrane in the device

J. Munoz et al. (2006)

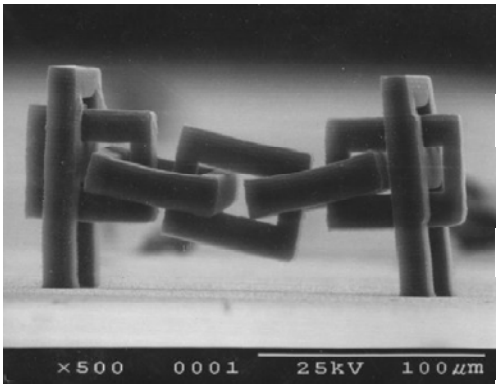
Extended Mold Techniques: Superlattice NanoPattern Transfer

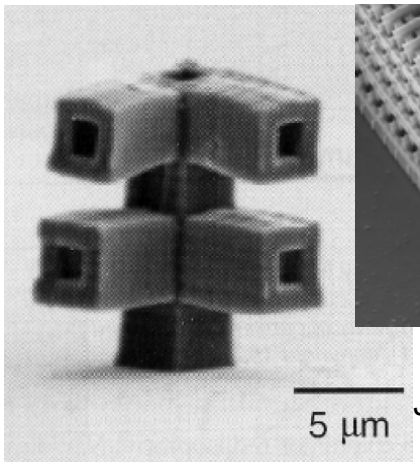


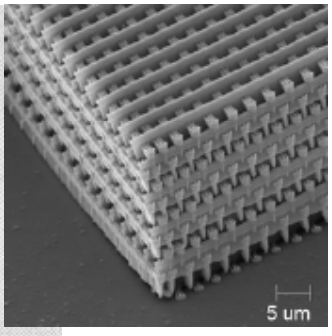


Melloch, Science (2006)

Two Photon





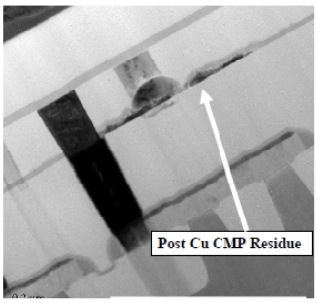


J. Perry, GaTech

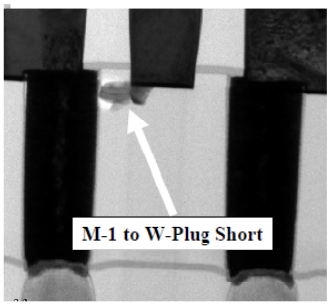
Chromophores with nonlinear absorbance
Absorbance only inside the focal point of two photons
Femtosecond laser beam of high intensity => polymerization in close proximity
~150 nm practical, ~60 nm possible. slows speed

Uses:
Photonic crystals?
MEMS / NEMS
Protein matrices for drug delivery

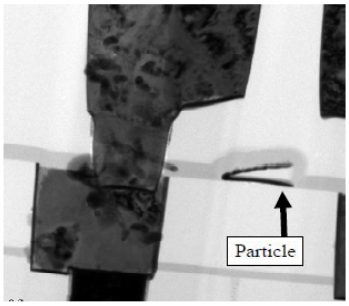
Defects



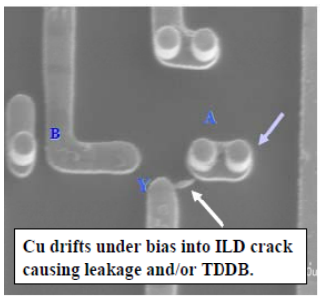
CMP Residue



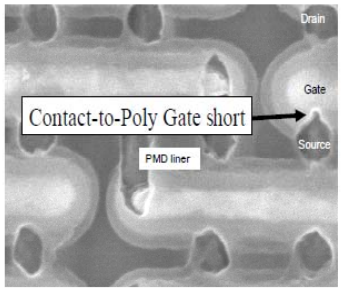
CMP Scratch



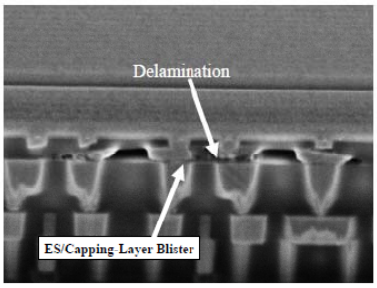
Particle



Low-k Crack



Contact-to-Gate Short

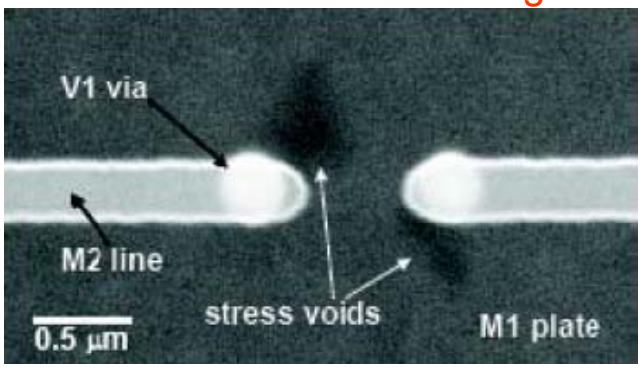


Interfacial Delamination

J.W. McPherson, IEDM(2005)

Defects

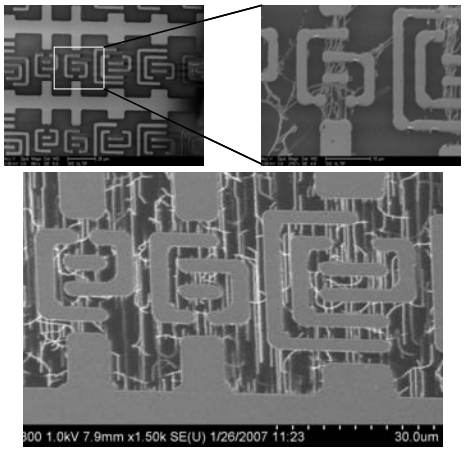
In Use in Old Technologies



Fabrication technology has to be consistent with needs of long term use: Reliability issues?

J.W. McPherson, IEDM(2005)

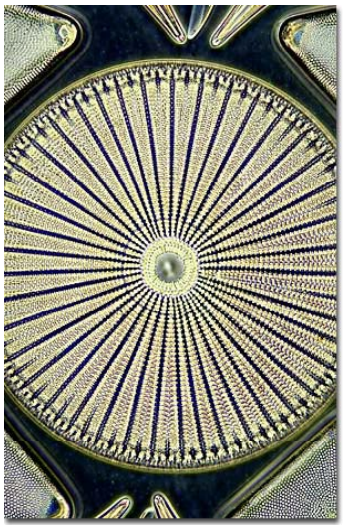
In New Technologies (CNT)

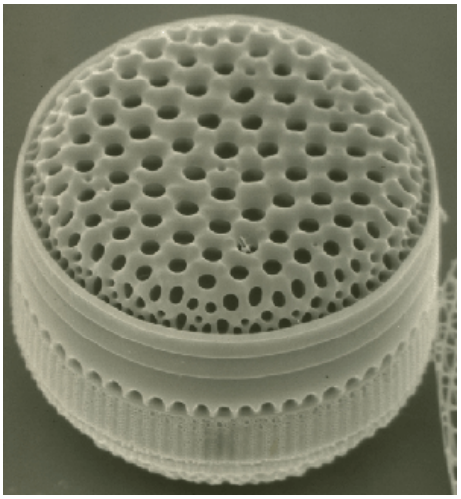


Fabrication technology has to provide sufficient reproducibility to begin with

S. Mitra (2007)

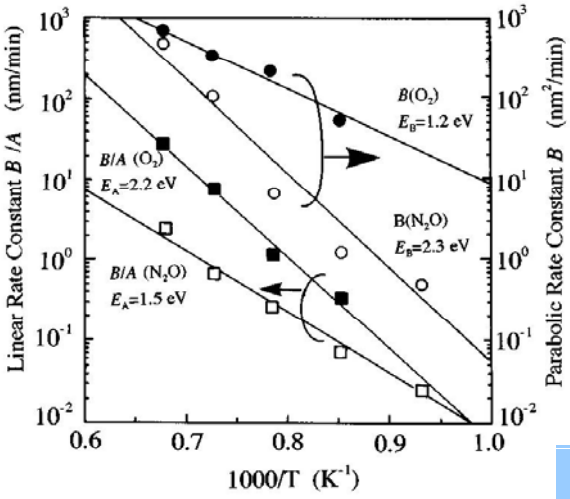
Natural Nanotechnology: BioNanofabrication





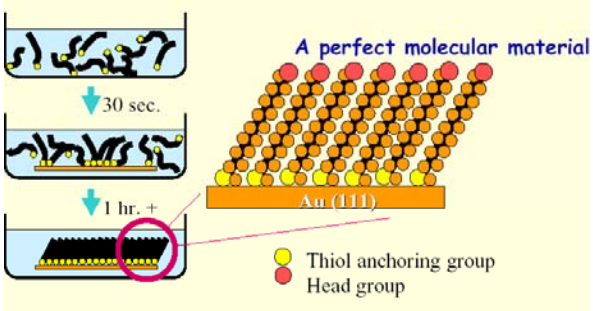
Energy Scales of Processing

Koyama et al. *Self Assembly: Oxide Growth*



ΔE = 1.5 to 2.5 eV (oxide growth)
ΔE > 2 eV for dopants used

Self Assembly: Molecular *Nuzzo et al.*



ΔE = 0.1 to 0.5 eV (self-assembly)

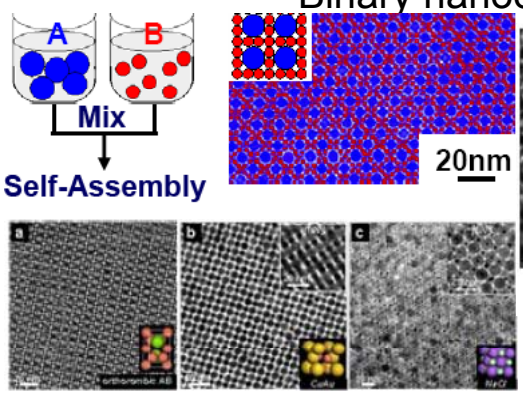
Vladiviroma et al.

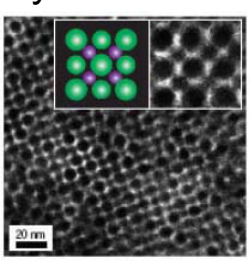
Probabilities proportional to *exp (-ΔE/kT)*
Smaller activation energies lead to larger variance
Short range and long range order

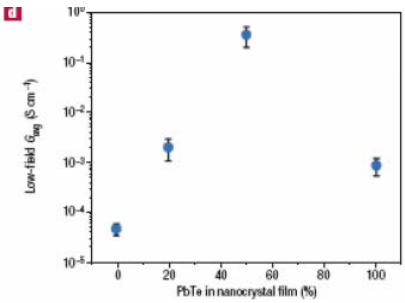
Energy	*Error Rates*
0.1 eV	~2×10^{-2}
0.5 eV	~5×10^{-9}
1.5 eV	~1×10^{-26}

Self Assembly

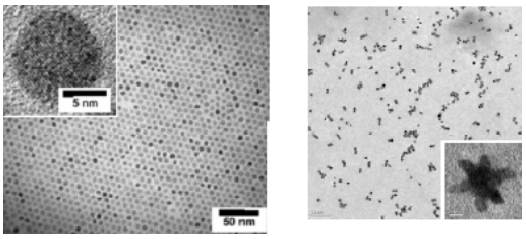
Binary nanocrystals







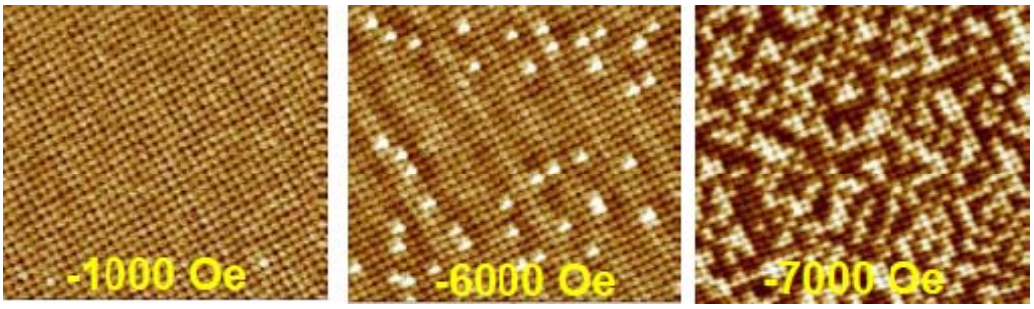
J Urban, IBM



Shvevchenko, Nature(2006)

Control of long-range order and structure
Understanding and prediction of nanocomposite properties
Complex materials

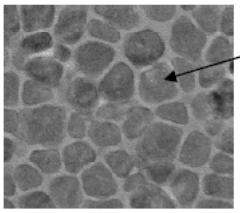
Magnetic



E. Fullerton (2005)

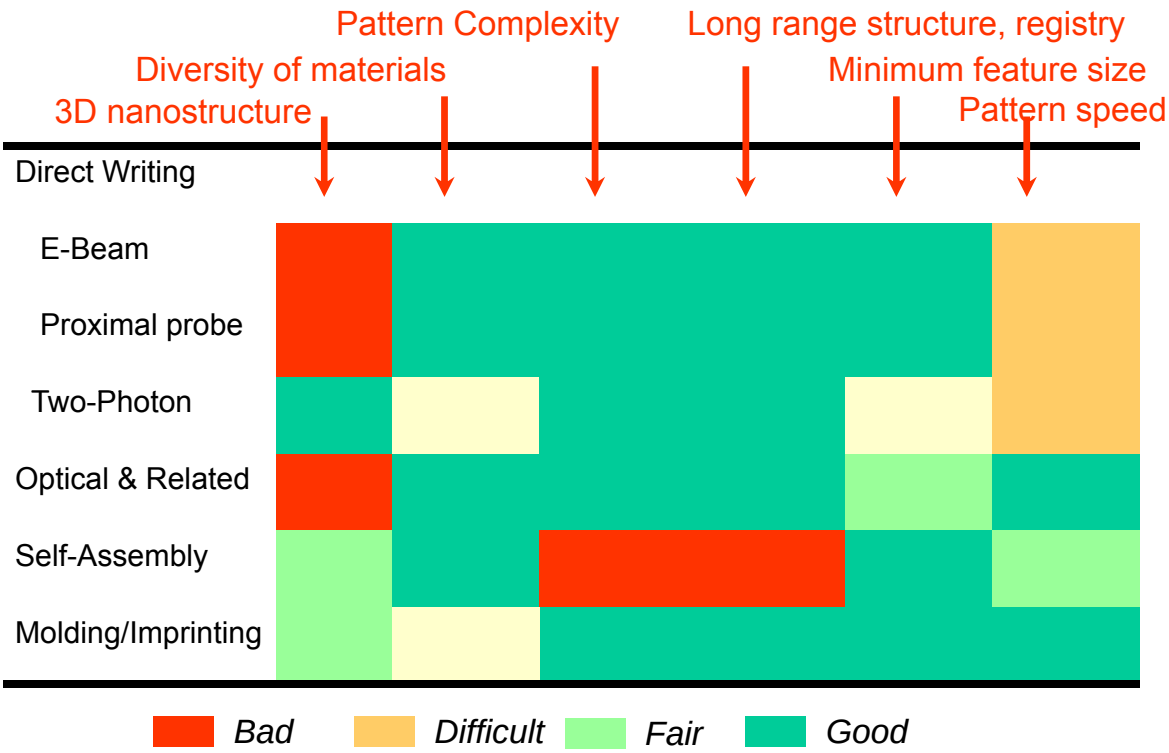
1Tb/in^2 requires 25nm bit cells ⇒12.5nm lithography for equal bits and space

Basic physics challenges



Magnetic energy
$E \sim K_U V > 55\ k_B T$

$K_U V = 100\ k_B T$ $\tau >$ age of universe
$K_U V = 45\ k_B T$ $\tau \sim 10$ years
$K_U V = 25\ k_B T$ $\tau \sim 7$ seconds



Challenges

- Three-dimensional nanostructure fabrication– <20nm feature size in 3D, ±1nm precision and reproducibility
  - High patterning speed, registry/order over large distances
  - Diverse materials palette – metal, semiconductor, dielectric, high-index, molecular
- Using nanostructures at the macro scale– Contacting/interconnecting large numbers of nanoscale objects
  - Integration of nanostructures with CMOS technology
  - High-throughput patterning, e.g., roll-to-roll or other large-volume production
- Complex nanocomposite materials and device structures– Predicting, engineering μ, ε, σ, κ, etc. in complex nanocomposites
  - Large area/volume assembly of nanocomposites, long-range structure/order, etc.

So, While there are Challenges

History is full of periods of saturation followed by rapid changes

Because we are never satisfied

So keep asking for more

3D with multi-photon (Germany)