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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Nanoscale Devices
Electronics
Large Area
Energy Conversion

Physical
Optics
Mechanical
Chem. & Bio.
Integration

Physical & Chemical Structural Control
Material – bulk & surface
Size, registration, alignment,
Cost Effective & Defect Tolerant

nm
m

Zero Mode
100 nm thick shaft
1 μm thick mass loading
Flexible
Complexity of Fabrication: Three-Dimensional Electronics

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**

MC simulation of 80 nm contact hole in EUV

J. Cobb, Proc. SPIE
**Photons**

436 365 248 193 157 13 nm

XRay: Resolution limited by $\lambda$, mask-wafer gap and Xray generation

Laearly free of thin film effects but difficult infrastructure

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**Charged Particles: Electron Beam Lithography**
**Electron-Beam Lithography**

Memories & Transistors

Most interesting working examples at nanoscale, but slow

**Scanned Probe: Atom by Atom**

note waves

D. Eigler, IBM Almaden
**Scanned Probe Techniques: Dip Pen**

Piner et al., Science (1999)

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**Ink Jets?**


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**Thermal NanoImprint**

1. Imprint
   - Press Mold

2. Pattern Transfer
   - RIE

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
   Template
   Plastic
   Several levels and back side alignment are possible

B) Thin film
The stamp geometry defines the flow pattern the substrate undergoes.

**Negative Master**

**Positive Master**

Contact: Avoiding sticking?
Biology Applications

Embossed and assembled device

CNC machined master

Caco-2 cells growing on a membrane in the device

J. Munoz et al. (2006)

Extended Mold Techniques: Superlattice NanoPattern Transfer

Two Photon

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
Contact-to-Gate Short
Interfacial Delamination

J.W. McPherson, IEDM(2005)
Defects

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

Fabrication technology has to provide sufficient reproducibility to begin with

J.W. McPherson, IEDM(2005)
S. Mitra (2007)

Natural Nanotechnology: BioNanofabrication
Energy Scales of Processing

Koyama et al.  Self Assembly: Oxide Growth

\[ \Delta E = 0.1 \text{ to } 0.5 \text{ eV (self-assembly)} \]

Vladiviroma et al.

\[ \Delta E = 1.5 \text{ to } 2.5 \text{ eV (oxide growth)} \]
\[ \Delta E > 2 \text{ eV for dopants used} \]

Smaller activation energies lead to larger variance
Short range and long range order

Probabilities proportional to \( \exp \left( -\frac{\Delta E}{kT} \right) \)

Tiwari_Fabrication_NSTI – June 4, 2008

Self Assembly

Binary nanocrystals

J Urban, IBM

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

1Tb/in² requires 25nm bit cells ⇒ 12.5nm lithography for equal bits and space

**Basic physics challenges**

\[ E \sim K_{ij}V > 55 k_B T \]

- \( K_{ij}V = 100 k_B T \), \( \tau > \) age of universe
- \( K_{ij}V = 45 k_B T \), \( \tau \approx 10 \) years
- \( K_{ij}V = 25 k_B T \), \( \tau \approx 7 \) seconds

**Direct Writing**

- **E-Beam**
- **Proximal probe**
- **Two-Photon**
- **Optical & Related**
- **Self-Assembly**
- **Molding/Imprinting**

**Pattern Complexity**

- Diversity of materials
- Long range structure, registry
- Minimum feature size
- Pattern speed

**Graph**

- **Bad**
- **Difficult**
- **Fair**
- **Good**

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**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 $\mu$, $\epsilon$, $\sigma$, $\kappa$, etc. in complex nanocomposites
  - Large area/volume assembly of nanocomposites, long-range structure/order, etc.

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**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