Nanoscale Issues in Materials & Manufacturing

ENGR 213 Principles of Materials Engineering
Module 2: Introduction to Nanoscale Issues
Top-down and Bottom-up Approaches for Fabrication

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Primer on manufacturing processes

- **Bottom-up self assembly (wet chemistry)**
  - biomimetic, controlled

- **Top-down assembly (lithography and derivatives)**
  - dip-pen lithography
  - soft lithography and nanoscale printing
  - e-beam and deep UV lithography

- **Other production processes**
  - vapor deposition
  - evaporation
  - combustion
  - thermal plasma
  - milling
  - cavitation
  - coating (spin or dip)
  - thermal spray
  - electrodeposition
Module 2: Nanoscale Issues

- Top-down Approaches to Fabrication
- Bottom-up Approaches to Fabrication
Two principal approaches

**Top-Down**
- Miniaturizing existing processes at the Macro/Microscale
- Traditional approach in industrial applications
- E.g. Lithography, backbone of computing systems

**Bottom-Up**
- Assembling structures from the atomic/molecular level
- Novel approach, conceptually imitating nature
- E.g. chemical self-assembly
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Top-down Approaches to Fabrication
Lithography in the Arts

- Invented by Alois Senefelder in 1798
- Process has been used for book illustrations, artist's prints, packaging, posters etc.
- In 1825, Goya produced a famous series of lithographs titled “The Bulls of Bordeaux”.
- In the 20th and 21st century, becomes an important technique with unique expressive capabilities in the Art field.
How Lithography started

- Lithography (Greek for "stone drawing") relies on the fact that water and grease repel
- Draw a pattern onto a flat stone surface with a greasy substance
- Paint the printing ink onto the stone
- While the stone background absorbs water, the greasy substance retains wet ink on top
- Press paper against the stone to transfer the pattern
- Positive! Repeatable!
Lithography, to date

- Miniaturized computing circuits require mass manufacturing of small features $\Rightarrow$ push lithographic approach to new limits
- Some lithography approaches for manufacturing
  - Optical lithography (including ultraviolet)
  - X-Ray lithography
  - Electron Beam lithography
  - Ion Beam lithography
  - “Dip-Pen” lithography
  - ...

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Optical/UV Lithography

- Workhorse of current chip manufacturing processes
- Limited by wave length of light employed
- Smaller features ⇒ reduce wave length ⇒ UV light

Here is how it works
Optical Lithography

UV UV UV UV UV UV UV

Mask
Photoresist
Si - Substrate
Optical Lithography

Development
Optical Lithography

Lift-Off
Example: Pentium III

Low Magnification

High Magnification
Lithography
Fundamental Limitations

• Smallest Feature Size is limited by wave length of light used
• Currently deep UV light is used to produce sub-μm line widths
• Moving into X-ray may allow further reduction
• This has practical complications, e.g. lenses
X-Ray Lithography Example

Typical structures made by deep x-ray lithography. Gear-shaped structures are used in air turbines, as encoders, stepper motor rotors, etc. High aspect ratio rectangular structures can be used for channel plate detectors, for example.
E-Beam Lithography

- Smallest Feature Size of optical lithography is limited by wave length of light
  - Use a smaller wave length!
  - Use electrons!
  - Quantum Mechanics ⇒ all particles have a wave length
  - Higher energy ⇒ lower wave length

Example
Electron Beam Lithography

Electron beam
Electron Beam Lithography
Electron Beam Lithography
Electron Beam Lithography

Development
Electron Beam Lithography
Electron Beam Lithography

Lift-Off
Electron Beam Lithography

Spin-Coating
- TTO
- glass
- PMMA 950 kamu, 2%
- 1100 μm
- rotating speed 5000 RPM
- (baking 8h, 170°C)

Exposure
- dot dose 0.03 pC
- (current 100 pA, dwell-time 0.3 ms)

Development
- developer
- (plasma cleaning, 30s)
- e.g. 30 nm
- speed 10 Å/s

Metal evaporation

Lift-Off
- Acetone
- 2.5 h, 50°C
- (plasma cleaning, 1m Ag, 2m Au)
Current Capabilities

• Use either dedicated e-beam writer or SEM (Vacuum environment)
• 30nm line width is straightforward
• <5nm can be achieved with conventional techniques
• <1nm line width is envisioned with innovative tricks
• Problem: Massive parallel circuitry difficult
Ion Beam Lithography Example
Dip-Pen Lithography

[Diagram showing an AFM tip and a printing tip with a 100 nm scale]
dip-pen lithography
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Bottom-up Approaches to Fabrication
Bottom-Up – Why?

- Top down is reaching limits
- Nature does not work top-down
- Scientists like to imitate nature
Bottom-Up – How?

• Molecular Assembly
  • Self-Assembly
  • “Assisted” through external parameters (e.g. fields, catalysts, etc)
• Biological Assembly
Self Assembly

coordinated action of independent entities

under distributed (i.e., non-central) control

to produce a larger structure or to achieve a desired group effect
Self Assembly

Making What?

Benzene, $C_6H_6$
Molecular Electronic Wires and Nanometer-Scale, Quantum-Effect Switches

- Molecule can act as wire or as resonant tunneling diode
- Methylene groups create “barriers” along a molecular wire to control transmission of electrons through a quantum well

- Advantages:
  - Molecules much smaller and every one is exactly alike
  - Easily can be made in vast numbers ($10^{23}$ at a time)

NOTE: Figure adapted from descriptive material provided by Prof. James Tour of the University of South Carolina.
Self Assembly

Other Self Assembly Areas

- Regular structured devices (optics)
- Nanocomposite fabrication
- Chemical sensors
- Wiring matrices (high density RAM)
- Chemical reactors
- Modular positioners
- Light-emitting diodes
- Optical storage materials
- Biosensors
- Drug-delivery materials
Ethical Consideration
Add Particles to Bulk Materials

How do we keep ‘nano’ character during processing?

Consolidation of Metals

Must stay below recrystallization temperatures.

Mixing with Polymers

Blend particles with resin or melted polymer.
Equal Channel Angular Extrusion

- Solid state processing at low to room temperature.
- Intense plastic deformation in shear works the material.
Equal Channel Angular Extrusion
ECAE Effect

- Nanoparticles become bulk material with larger but nanoscale grain sizes.