I. Nanofabrication and Characterization
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I. NANOFABRICATION AND CHARACTERIZATION

- Chap. 1: Nanolithography
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- Chap. 3: Scanning Probe Microscopy
I. Nanofabrication and Characterization: TOC

- Chap. 1: Nanolithography
- Chap. 2: Self-Assembly
- Chap. 3: Scanning Probe Microscopy

Chap. 1: Nanolithography

1.1. Introduction
1.2. Resists and Masks
1.3. Photon-Based Lithography
1.4. Electron Beam Lithography
1.5. Ion Beam Lithography
1.6. Emerging Nanolithographies

The Si revolution...

First Transistor
Bell Labs (1947)

Si integrated circuits
Texas Instruments (~1960)

Modern ICs

IC manufacturing

- Silicon Wafer
- Pattern Being Printed onto Wafer
- Resin (PR)
- Light
- Photoresist (SiOx)
- Silicon Dioxide (SiOx)
- Silicon Wafer (Si)
- Polishing Water (Si)
- Etching Chip Section
- Stripped Chip Section
- Silicon Dioxide (SiOx)
- Additional Layer (such as phosphorus, doped Silicon)

More? Check out:
http://www.pbs.org/transistor/background1/events/miraclemo.html
http://www.ti.com/corp/docs/company/history/firstic.shtml

Source: http://www.cae.wisc.edu/~chauhan/nanolith2.shtml
The need of micropatterning

The batch fabrication of microstructures requires a low-cost, high throughput surface patterning technology.

Overview of photolithography

Photolithography consists of patterning substrate by employing the interaction of beams of photons or particles with materials.

Photolithography is widely used in the integrated circuits (ICs) manufacturing.

The process of IC manufacturing consists of a series of 10-20 steps or more, called mask layers where layers of materials coated with resists are patterned then transferred onto the material layer.

Overview of photolithography (ctnd.)

A photolithography system consists of a light source, a mask, and a optical projection system.

Photoresists are radiation sensitive materials that usually consist of a photo-sensitive compound, a polymeric backbone, and a solvent.

Resists can be classified upon their solubility after exposure into: positive resists (solubility of exposed area increases) and negative resists (solubility of exposed area decreases).
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Positive vs. negative photoresists

Threshold and clearing doses

Solubility vs exposure dose of a positive photoresist

“contrast” \( \gamma \) of resist :

\[
\gamma = \frac{1}{\log \left( \frac{D_c}{D_0} \right)}
\]

fraction remaining = \(-\gamma \cdot \log \left( \frac{\text{Dose}}{D_c} \right)\)

Threshold and clearing doses: example

Question:
A positive photoresist possesses a contrast \( \gamma = 5 \), and a clearing dose \( D_c = 300 \text{ mJ/cm}^2 \). What dose is required to dissolve 50 % of the resist thickness ?

Answer: The resist will have a threshold dose \( D_0 \):

\[
D_0 = D_c \cdot 10^{-\frac{\gamma}{2}}
\]

\[
= 300 \cdot 10^{-\frac{5}{2}}
\]

\[
= 189 \text{ mJ/cm}^2
\]

The contrast curve is analytically given by:

fraction remaining = \(-\gamma \cdot \log \left( \frac{\text{Dose}}{D_c} \right)\)

0.5 = \(-5 \cdot \log \left( \frac{\text{Dose}}{300} \right)\)

Dose = 237 \text{ mJ/cm}^2

The resist will be 50 % dissolved when using a dose of 237 \text{ mJ/cm}^2
Types of photolithography

- Contact Printing
- Proximity Printing
- Projection Printing

Resolution of photolithography

Contact lithography limited by Fresnel diffraction:

\[ W_{\text{min}} = \sqrt{\lambda g} \]

where \( \lambda \) is wavelength employed and \( g \) is mask-resist gap.

Projection lithography limited by Rayleigh’s criterion:

\[ R = \frac{k_1 \lambda}{\text{NA}} \]

where \( \lambda \) is wavelength employed, NA is numerical aperture of lens (NA = sin \( \alpha \)), and \( k_1 \) is a constant (typically \( k_1 = 0.6 - 0.8 \)).

Resolution of photolithography: example

**Question:**
An x-ray contact lithography system uses photons of energy of 1 keV. If the separation between the mask and the wafer is 20 \( \mu \)m, estimate the diffraction-limited resolution that is achievable by this system.

**Answer:**

The energy \( E_p \) of photons is related to their wavelength \( \lambda \) through:

\[ E_p = \frac{hc}{\lambda} \]

where \( h = 6.626 \times 10^{-34} \text{ m}^2 \text{ kg/s} \) is Planck’s constant, and \( c = 3 \times 10^8 \text{ m/s} \) is the speed of light.

Thus, the wavelength of the photons employed is:

\[ \lambda = \frac{6.626 \times 10^{-34} \cdot 3 \times 10^8}{1000 \cdot 1.6 \times 10^{-19}} \]

\[ \lambda = 1.24 \text{ nm} \]

The minimum feature size that can be resolved is:

\[ W_{\text{min}} = \sqrt{\lambda g} \]

\[ W_{\text{min}} = \sqrt{1.24 \times 10^{-15} \cdot 20 \times 10^{-6}} \]

\[ W_{\text{min}} = 157 \text{ nm} \]

Resolution of photolithography (ctnd.)
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Diffraction and other optical effects likely to limit the resolution of "standard" DUV ($\lambda = 193$ nm) lithography to the 75-100 nm range.

Upcoming generation (2005) to employ DUV ($\lambda = 193$ nm) based 65 nm lithography and 35 nm gate lengths.

Intel lithography roadmap will eventually skip $\lambda = 157$ nm technology and pursue well into the sub-100 nm region through EUV ($\lambda = 13.5$ nm) (~2009)

Exploratory research in the sub-100 nm region may also be accomplished through alternate patterning techniques such as x-ray-, ion-, and electron beam-lithography.

Intel lithography roadmap (Nov 2004)

EUV lithography system

EUV Systems to employ reflective instead of refractive optics
EUV lithography system (ctnd.)

50 nm lines fabricated with EUV lithography (~1999)
30 nm features now routinely achieved

EUV lithography system (ctnd.)

One in every home...

X-Ray lithography

- Diffraction limits lithography resolution to $\lambda/2$
- Obvious solution: use lower wavelengths sources
- DUV and EUV approaching standardization
- X-Ray lithography still at "exploratory" stage
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Plasma X-Ray source

Electron beam lithography

A beam of electron instead of photons

Advantage: Fast turn-around time
Disadvantage: Slow throughput

More? Google it! Also, check out R.F.W. Pease, Stanford

Source: SAL, Inc.
Electron beam lithography system

Applications of electron beam lithography
Mainly employed for the fabrication of photomasks
Also used to write patterns directly on wafer

Scattering phenomena in e-beam litho
Scattering phenomena dictate resolution
Better resolution achieved at higher beam energies

E-beam fabricated nanostructures
- 30 nm thick poly(methyl methacrylate) (PMMA) is spin-cast on Si substrate.
- Exposure to e-beam along vertical lines spaced 50 nm apart, breaks polymer bonds and increases solubility.
- 10 nm lines are dissolved away by a solvent.
Electron beam projection lithography (EPL)

SCALPEL System (Lucent Technologies)

Electron beam projection lithography (ctnd.)

Principle of continuous membrane EPL

Structures produced by EPL

Technology was a serious contender for future sub-70 nm nodes
Relatively low throughput and high cost of mask precluded its viability
Eventually abandoned (~2001) in favor of EUV ($\lambda = 13.5$ nm) optical systems

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Ion beam lithography

- Advantages of ion beams:
  - Enhanced resists sensitivity
  - Can be focused to narrower linewidth
  - Reduced scattering
  - Allows hybrid processes such as ion-induced etching and implantation

Focused ion beam lithography

- FIBL components:
  - Ion source
  - Ion optics column
  - Sample displacement table

- Specifications:
  - Accelerating voltage 3-200 kV.
  - Current density up to 10 A/cm².
  - Beam diameter 0.5-1.0 μm.
  - Ions: Ga⁺, Au⁺, Si⁺, Be⁺ etc.

Liquid metal ion sources

- Provides sub-micrometer beam with good current density (1-5 A/cm²) for metals with a relatively low melting temp and vapor pressure (ie. Ga, In, Sn etc.).

FIB fabricated nanostructures
Effects of the ion beam on the substrate:
- Displacement of atoms.
- Emission of electrons.
- Chemical effect like change of solubility of the resist.
- Sputtering of substrate atoms by low energy ions.
- May result in resist heating as high as 1500° C

Alternate Nanolithography Techniques
- Micro-contact Printing
- Nanoimprint Lithography
- Scanned Probe Lithography
- Dip-pen Lithography

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Micro-contact printing
1) Application of ink to stamp
2) Application of stamp to surface
3) Removal of stamp
4) Residues rinsed off

Source: IBM Zurich
Micro-contact printing

Selecting growth of neurons on printed surfaces

Biological interactions that underlie neuron cell attachment and growth are being employed to produce defined networks of neurons.

Microcontact printing has been used to place chemical, biochemical, and/or topographical cues at designated locations.

Important potential for the interfacing of solid state electronics with nerve cell biology, and for the fundamental electrical studies of single nerve cells.

Source: Craighead Group, Cornell

Alternate Nanolithography Techniques

- Micro-contact Printing
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Nanoimprint Lithography

Consists of pressing a mold onto the resist above its glass transition temperature $T_g$.

More check out S. Y. Chou, Princeton
SiO₂ pillars with 10 nm diameter, 40 nm spacing, and 60 nm height fabricated by e-beam lithography. Master can be used tens of times without degradation.

Mask is pressed into 80 nm thick layer of PMMA on Si substrate at 175°C (T<sub>g</sub>=105 °C), P= 4.4 MPa. PMMA conforms to master patterning, resulting in ~10 nm range holes.

Reactive ion etching is used to cut down resist thickness until shallow regions are completely removed. Ti/Au is deposited onto resist. Resist and metal-coating is removed by solvent leaving behind metal dots where resist had been removed.

- Micro-contact Printing
- Nanoimprint Lithography
- Scanned Probe Lithography
- Dip-pen Lithography
Scanned Probe Lithography

Fabrication of CMOS gate using SPM lithography

Alternate Nanolithography Techniques

- Micro-contact Printing
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Dip-pen lithography

Source: Quate Group, Stanford

Source: Quate Group, Stanford

Source: Mirkin Group, NWU

Source: Mirkin Group, NWU
Dip-pen lithography

A) Ultra-high resolution pattern of mercaptohexadecanoic acid on atomically-flat gold surface. B) DPN generated multi-component nanostructure with two aligned alkanethiol patterns. C) Richard Feynmann's historic speech written using the DPN nanoplotter.

Source: Mirkin Group, NWU